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Surface-Based Observations of Contrail Occurrence Frequency Over the U.S., April 1993 - April 1994

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Summary

Surface observers stationed at 19 U.S. Air Force Bases and Army Air Stations recorded the daytime occurrence of contrails and cloud fraction on an hourly basis for the period April 1993 through April 1994. Each observation uses one of four main categories to report contrails as unobserved, non-persistent, persistent, and indeterminate. Additional classification includes the co-occurrence of cirrus with each report. The data cover much of the continental U.S. including locations near major commercial air routes. The mean annual frequency of occurrence in unobstructed viewing conditions is 13 percent for these sites. Contrail occurrence varied substantially with location and season. Most contrails occurred during the winter months and least during the summer with a pronounced minimum during July. Although nocturnal observations are not available, it appears that the contrails have a diurnal variation that peaks during mid morning over most areas. Contrails were most often observed in areas near major commercial air corridors and least often over areas far removed from the heaviest air traffic. A significant correlation exists between mean contrail frequency and aircraft fuel usage above 7 km suggesting predictive potential for assessing future contrail effects on climate. Additional surface observations and a concerted satellite observation effort are needed to accurately assess the climatic effect of aircraft condensation trails.

Introduction

Condensation trails or contrails have become a common feature in the Northern Hemisphere since World War II. These anthropogenic clouds represent the most visible byproduct of jet fuel combustion at high altitudes. The mechanism for contrail formation is complex, depending on a variety of parameters including the type of jet engine, the sort of fuel, and the ambient temperature and humidity (Karcher, 1994; Schumann, 1996). The exhaust may produce numerous sulfate aerosols that act as cloud condensation nuclei which initiate tiny droplets that subsequently freeze. The resulting cloud usually contains large concentrations of small ice crystals (e.g., Murcray, 1970). They generally form at temperatures less than -30°C at high relative humidities or below -50°C at moderate to low moisture levels (e.g., Appleman, 1953). If formed in clear air, contrails can spread, developing into cirrus indistinguishable from natural clouds. Their persistence and growth depend on the available moisture and ambient temperature. When aircraft fly through existing clouds they can produce contrails or distrails (cloud-free trails) depending on the conditions (e.g., Scorer, 1972). In either case, they produce an immediate effect by altering the microphysical properties of the existing cloud.

Increases in cloud cover or cloud particle concentrations due to contrails can alter the local radiative balance by reflecting more solar radiation and absorbing and emitting longwave infrared radiation (e.g., Kuhn, 1970). The overall effect of contrails on climate depends on a number of factors including frequency and timing of occurrence, areal coverage, lifetime, altitude, location, and microphysical properties. The upper troposphere is a relatively clean (aerosol-free) environment so that the addition of high concentrations of cloud condensation nuclei have the potential for making a larger impact than they would in the lower troposphere. With commercial air traffic expected to increase by more than 200 percent by 2015 (Baughcum, 1996), the effects of aircraft exhaust on the atmosphere have become a subject of considerable interest leading to the NASA Atmospheric Effects of Aircraft Program (AEAP) which has sponsored the Subsonic Assessment (SASS) Project (Thompson, et al., 1996). One of the goals of the AEAP SASS Project is to evaluate the effect of contrails on climate. This paper presents the results of a study of contrail occurrence frequencies over the U.S based on recent surface observations.

Background

Evaluations of contrail coverage or occurrence have been made either directly or indirectly from surface and satellite observations since the 1980's. These efforts have been sporadic and generally confined to a few particular areas. Examples of inferred contrail coverage include the conclusions of Chagnon (1981) and Angell et al. (1984) that decreased sunshine and increased cloudiness since 1960 and between 1950 and 1972, respectively, are attributable to contrails. Seaver and Lee (1987) found that the number of cloudless days over the continental United States (US) decreased significantly for the period 1950-1982 compared to 1900-1936 possibly due to the appearance of contrails during the latter period. In a follow-up study, Angell (1990) found that US cloudiness continued to increase through 1988 while sunshine duration decreased. The relative magnitude of the change in sunshine was not as great as the cloudiness increase. This finding suggests an increase in thin cirrus due, most likely, to contrail-generated cirrus. Significant decreases in insolation were also observed in Germany during the past 20 to 40 years. Weber (1990) suggested that increased cyclonic activity increased cloud cover and decreased sunshine over Germany. Liepert et al. (1994) estimated that contrail coverage, based on a surface study of contrails over a single site, was too small to account for the diminished sunshine. Discrepancies between the conclusions of these various studies highlight the uncertainties in the current assessment of the climate impact of contrails.

Satellite data have been used in a variety of ways to study contrails over larger areas and longer time periods. Joseph et al. (1975) used two photographs from an Earth resources satellite to demonstrate the detection of contrails from space over the Mediterranean. From preliminary studies of Defense Meteorological Satellite Program (DMSP) imagery, Carleton and Lamb (1986) found that infrared (IR) data were more valuable for detecting contrails than visible data. Lee (1989) showed that brightness temperature differences between the split window channels on the NOAA Advanced Very High Resolution Radiometer (AVHRR) could be used to detect contrails more easily than simply examining infrared window channel imagery. DeGrand et al. (1990) used the single-channel IR imagery from the Sun-synchronous DMSP satellites to develop a climatology of contrail occurrence over US for the period 1977-1979. Although they provided some estimates of the relative magnitudes of the mean seasonal and diurnal cycles over US, the actual frequencies of occurrence were not reported. Engelstad et al. (1992) added image processing techniques to the brightness temperature difference imagery to automatically detect contrails without human intervention. Their method, however, has not yet been applied to significant amounts of satellite data. Schumann and Wendling (1993) also developed an automated technique but they have reported only preliminary results from 99 AVHRR images over central Europe. Bakan et al. (1994) used visual analysis of thousands of quicklook AVHRR IR images taken over the northeast Atlantic and Europe to estimate contrail cloudiness for 1979-1981 and 1989-1992. They found a distinct seasonal cycle with a southward displacement of the contrail maximum during winter. Maximum contrail coverage in their analysis occurred during summer centered along the North Atlantic air routes. The coverage increased in that area during the 10-year interim. Similar analyses over the air corridors of the US have not yet been performed. The surface observations reported here represent the first step to better defining the contrail-based cirrus coverage over the US.

Nomenclature

AEAP	Atmospheric Effects of Aircraft Program
AFB	Air Force Base
AVHRR	Advanced Very High Resolution Radiometer
c	mean annual contrail frequency
DMSP	Defense Meteorological Satellite Program
f	mean annual fuel usage above 7 km, 10^6 lbs
IR	infrared
LAFB	Langley Air Force Base
LT	local time
NASA	National Aeronautics and Space Administration
NOAA	National Oceanographic and Atmospheric Administration
R	linear correlation coefficient
RH	relative humidity
SASS	Subsonic Assessment
T_f	monthly average temperature at mean flight level
U.S.	United States
US	Continental United States
UTC	Universal Coordinated Time
WPAFB	Wright-Patterson Air Force Base
z_p	monthly mean tropopause altitude

Data

The U.S. Air Force established a unique network of surface observers to develop a climatology of contrail occurrences over the US for studying contrail formation and forecast models. This dataset was made available to NASA in its raw form: log sheets of hourly meteorological observations with distinct contrail codes or special log sheets used only for recording the contrail codes. The contrail observations were listed as one of four classifications: no contrails, non-persistent contrails, persistent contrails, and indeterminate contrails. In addition, each classifier was qualified as being with or without cirrus. Finally, the contrail observations were not always taken even though weather data were recorded. Thus, there is a no-observation category yielding a total of nine possible contrail classifications. These contrail codes as well as the sky cover in tenths were transposed to a computer spreadsheet format for additional analysis.

The observation network, comprising 19 U.S. Air Force Bases and Army Air Facilities, was spread over the US (Figure 1) to determine the spatial variability of contrail formation. The nominal period of observation for this special effort was April 1, 1993 through March 31, 1994. The actual period varied with reporting station. The earliest month is January 1993, while the latest is May 1994. As many as 15 and as few as 7 months of data were taken at a given location. Most sites recorded data for 13 months. Contrail observations were taken every hour at the same time as the standard meteorological data, but only during the daytime. Nocturnal data were not recorded because of the ambiguities associated with taking high-cloud observations in the dark (e.g., Hahn et al., 1995). Sky cover was recorded at most locations for much of the period, although the special contrail logs were the only available data for a few stations. The indeterminate category was selected if the sky was overcast below the level of cirrus clouds. Persistent contrails were defined for this study as those extending at least several miles behind the aircraft with no tendency for dissipation. A nonpersistent contrail is defined as one that tends to evaporate and only extends a short distance behind the aircraft.

Figure 2 shows an example of the raw data in the form of a coded summary of the hourly contrail observations for Langley Air Force Base (LAFB) taken during December 1993. At night, no contrail data were taken although cirrus occurrences were recorded. Indeterminate contrail conditions dominated during at least 10 days, especially December 4, 5, 15, 16, 28, and 29. A period of persistent contrails with cirrus on the 2nd was followed the next day with sporadically persistent and nonpersistent contrails and no cirrus. A few temporary or nonpersistent contrails were seen early during December 6 followed by several hours without contrails or cirrus. After 1200 UTC, cirrus occurred every hour during the next day with a few temporary contrails and 2 hours of indeterminate contrails. The other significant periods of persistent contrails include December 9, 10, 14, 20, and 24. The total number of hours when contrails were or were not observed were 52 and 85, respectively. Persistent contrails account for 65 percent of all of the contrail observations. Of these, only 34 percent were unaccompanied by cirrus.

Figure 3 summarizes the 24-hour, daily observations over LAFB for the period from March 1993 through April 1994. The colors at the top of graph correspond to indeterminate (light gray) and contrail-free cases, while the black area in the middle registers the percentage of missing and nighttime data. Along the bottom of the graph, the colors refer to various contrail conditions including indeterminate contrails with cirrus (gray at bottom). No data were taken during November 1993 and January, February, and March 1994. Persistent contrails occurred most often during a given day in the spring during both 1993 (days 110-150) and 1994 (days 465-480) and least during the late summer of 1993 (days 190-220). This latter period also has the most observations of no contrails with cirrus.

Temperatures and humidities at the standard meteorological levels were taken from 12-hourly National Meteorological Center analyses. These data are available on a 2.5° latitude-longitude grid. They were bi-linearly interpolated to match the location of each surface site. Only data from July 1993 and January and April 1994 are considered here.

Results

The data for each of the categories exemplified in Figures 2 and 3 and for the cloud observations were averaged for each month and hour in Coordinated Universal Time (UTC).

Seasonal Variations

Examples of the monthly means are plotted in Figure 4 for LAFB. Contrails occurred most frequently during April 1993 with ~32 percent of the total observations (Figs. 4a). A similar number of contrail observations was reported during the following April. Nonpersistent contrails were most frequent during June 1993 and April 1994. The fewest contrails (~5 percent) were seen during July 1993 when cirrus clouds were most abundant. The worst viewing conditions were found during March and December 1993 when the indeterminate levels were greatest. Figure 4b combines the categories into four classes that do not consider the occurrence of cirrus. The indeterminate classifications, more easily discerned in this figure, generally correspond to the occurrence frequencies of 90 and 100 percent cloud cover (Figure 5a). If indeterminate data are removed and the classifications are normalized to the number of remaining observations, the relative temporal pattern of contrail occurrence remains much the same except for the substantial increase in contrails during December (Figure 4c). These normalized percentages may be a more accurate accounting of the contrails because the indeterminate data are almost equivalent to missing data. The months having the most clear days are October and December 1993 and April 1994 (Figure 5a). Results corresponding to Figure 4 are provided in Appendix A for each observing site. The missing data evident in Figure 5 for November 1993 and for January, February, and March, 1994 are not typical for most of the sites. Better sampling was obtained for 14 other sites.

Table 1 lists the mean contrail occurrences for each site and the corresponding period of observation. Figure 6 shows the means and standard deviations based on monthly averages of the combined persistent and nonpersistent contrails from data like those in Figure 4a which includes indeterminate data. The fewest number of persistent contrails occurred over Eglin AFB (3.6 percent) and Minot AFB (3.8 percent), while the greatest number were seen over Wright-Patterson AFB (WPAFB; 15.1 percent) and Edwards AFB (14.9 percent). If indeterminate cases are omitted, then contrails were most frequent over WPAFB (28.5 percent) and LAFB(19.9 percent). Without the indeterminate observations, the sites with the fewest persistent contrails are Eglin (5.1 percent) and Luke (5.4 percent) AFB's. Nonpersistent contrails were most often observed over Luke AFB (9.2 percent) and LAFB (~5 percent), while the fewest were seen over Kelly AFB. Both persistent and nonpersistent contrails are most likely to occur when cirrus clouds are present. The mean probability for seeing a contrail when cirrus are present is 24.8 percent, compared to only 7.3 percent when cirrus are not observed. Contrails are also more likely to persist when cirrus are present. When cirrus and contrails occurred together, 75 percent of the contrails were classified as persistent compared to 55 percent when cirrus were absent. The greatest monthly variability (Figure 6) occurs over McClellan AFB, while contrail occurrence over Eglin is consistently low from month to month.

Figure 7, which summarizes the results in Appendix A, reveals that the maximum contrail occurrence occurs between January (Figure 7a) and April (Figure 7b) for most sites. A notable exception is Minot AFB where October (Figure 7d) is the most favored month for contrails. Minimum contrail occurrence is generally found during July (Figure 7c). The seasonal variations in contrail events averaged for all sites are shown in Figure 8. If the events are referenced to the total number of observations (Figure 8a), then there is a distinct maximum during February and an apparent secondary peak during October. Although the October value is statistically different from the September mean, it does not differ significantly from the November result. Overall, contrails are scarcest during July. If indeterminate observations are excluded from the total (Figure 8b), the seasonal curve becomes smoother. The maximum occurs during March or between February and March with no secondary peak during October. Regional variability is considerable. In absolute terms, it is greatest during February. If computed relative to the mean occurrence values, the greatest geographical variability occurs during July and November.

Diurnal Variability

Figure 9 depicts the diurnal variations in contrail frequency over LAFB. The greatest number of contrails was observed (Figure 9a) during midmorning at 1400 UTC (0900 LT). A broad secondary maximum covers the period from 1800-2100 UTC. Normalization to the total number of observations (Figure 9b) reveals a substantial peak at 2400 UTC. This maximum may not be representative, however, because it is based on a limited sampling of ~110 observations (Figure 9a) that are confined to particular months. This number of observations is about half of the total between 1200 and 2200 UTC. The differences in hourly sampling are primarily due to changes in the day length with season. It is important to consider the sampling when examining these diurnal results. If only hours having more than 150 samples are considered, the peak contrail frequency remains at 1400 UTC and the lowest frequency of contrails is apparent at 1200 and 1700 UTC. When indeterminate data are removed (Figure 9c), the relative diurnal cycle is the same although the morning maximum is enhanced slightly. The primary minima occur at 1200 (0700 LT) and 1700 UTC (local noon). Plots of the mean hourly contrail statistics are provided in Appendix B for each observation site.

By excluding the indeterminate data and using only those hours with more than half the maximum number of hourly samples for each site, it is possible to determine the primary and secondary diurnal maxima in contrail occurrence. Here, the primary maximum is defined as that hour having the greatest contrail frequency. The secondary maximum is the hour with the next highest frequency that is at least 3 hours removed from the primary maximum. The amplitude of these maxima is half of the difference between a given maximum and the minimum divided by the mean total contrail occurrence. In Figure 8c, the primary peak at 1400 UTC is 39 percent and the minimum is 20 percent at 1800 UTC. The amplitude of this maximum is 40 percent because the mean is 24 percent (Table 1). The secondary peak at 1800 UTC with a magnitude of 19 percent may not be particularly significant. Table 2 summarizes the diurnal characteristics of contrail frequency for each site. Loring AFB has the greatest amplitude with a primary peak in the evening. The smallest amplitude is 23 percent at Barksdale AFB, also with an early evening maximum. The average primary and secondary amplitudes are 58 and 46 percent, respectively. Amplitude does not appear to have a longitudinal dependence. Plots of the primary and secondary maxima times in Figure 10 also show some interesting features. In Figure 10a, the primary maxima are concentrated between 1500 and 1800 UTC and between 2300 and 0100 UTC, while many of the secondary maxima occur between 1800 and 2300 UTC. When converted to local time (Figure 10b), the primary maxima cluster around 0900 and 1700 LT, while the secondary peaks primarily occur during the afternoon. Figure 11, a plot of the maxima as a function of longitude, shows that, except for Loring AFB, the times of primary maximum are found near 0830 LT over the eastern US, during the late morning or late afternoon over the central US, and during the early morning or late afternoon in the west. The secondary maxima generally fall in the afternoon except for some of the westernmost sites..

Cloud Cover

The fractional cloudiness frequencies and monthly mean areal cloud coverage are given in Figure 5 for LAFB. The monthly frequency of a given cloud fraction (Figure 5a) was discussed earlier. The mean annual diurnal variation of each fractional cloud amount is shown in Figure 5b. The times are given in UTC, but the abscissa scale is shifted such that the hour closest to local noon is at the center of the graph. In this particular case, cloud observations were taken for the complete diurnal cycle. Clear skies are most frequent near local midnight (5 - 8 UTC) and seen least often around local noon (17 - 21 UTC). Both fractional and overcast cloudiness follow a diurnal cycle complementary to the clear skies. The monthly mean cloudiness in Figure 5c varies from a low in June 1993 to a peak during March 1993. The missing months prevent a more complete determination of the annual cycle. Data corresponding to Figure 5 have been plotted in Appendix C for each site. No cloud observations were available at five sites: Griffis, Hill, Kelly, McClellan, and Tinker Air

Force Bases. Complete 24-hour sampling is available at the remaining sites.

The monthly mean cloudiness for the 14 sites with observations is summarized in Figure 12 with the mean US surface-observed cloud amounts from Hahn et al. (1986) for the period 1971- 1981. The average for both datasets is ~ 55 percent. In both cases, cloud amount peaks during the winter with a minimum during late summer and autumn although the annual range for the contrail dataset is ~26 percent compared to 12 percent from the US average. Figure 13 shows the monthly averages of mean cirrus frequencies. These results show that cirrus was observed over the surface sites least often during the winter and most frequently during the late autumn months. Thus, the cirrus frequencies are slightly out of phase with the corresponding cloud amounts. Overall, cirrus was observed in ~55 percent of the observations. Figure 13b also plots seasonal mean US cirrus frequencies based on surface observations during 1971-1980 (Hahn et al., 1984). The seasonal means correspond well with the present results for winter and spring. Cirrus clouds were observed 4 and 10 percent more often in the current dataset than in 10-year average for summer and autumn, respectively. The general agreement between the cloud amounts and cirrus frequencies suggest that the selected sites are representative of the US as a whole.

The mean monthly variations of persistent contrails with and without cirrus are shown in Figure 14. In general, both curves follow the total contrail seasonal trends seen in Figure 8b. The ratio of seasonal contrail frequencies with cirrus to those without cirrus are 3.1, 4.3, 3.6, and 5.1 for winter, spring, summer, and fall, respectively. These co-occurrence ratios are consistent with the minimum and maximum frequencies of cirrus in Figure 13b. Figure 15 shows the contrail frequencies as a function of coincident cloud amount averaged for the sites reporting hourly cloud amounts. Few persistent contrails were seen in otherwise clear skies (Figure 15a), while cloud amounts near 75 percent correspond to the most frequent occurrence of persistent contrails. This result is consistent with the frequent occurrence of contrails with cirrus. Conversely, non-persistent contrails were observed most often in almost clear skies (Figure 15b) suggesting that the nonpersistent contrails form primarily in drier conditions. When all contrails are considered, the maxima arise in mostly cloudy and partly cloudy conditions with minima in almost clear or overcast conditions and when cloud fraction is around 50 percent (Figure 15c).

Discussion

The occurrence of contrails is primarily determined by two factors: the presence of aircraft exhaust and the ambient conditions at flight level. An observation of a contrail requires both proper timing and a sufficient line of sight from the observer to the contrails. These factors and their relationships to the observations are discussed here.

Aircraft Fuel Use

A preliminary dataset of fuel usage was developed from the estimates of commercial scheduled and other non-scheduled and military air traffic by Baughcum et al. (1993) for May 1990. The data were compiled on a 1° x 1° latitude-longitude grid with a vertical resolution of 1 km. It was assumed that the May data are representative of the annual mean. A later analysis by Baughcum (1996) confirms that assumption. Figure 16 shows the mean fuel usage as a function of altitude for the nine 1° boxes centered over the 19 contrail sites. The maximum fuel use above the boundary layer occurs at flight levels between 10 and 12 km (33,000 - 38,000 ft) for all of the sites. The low-altitude fuel is primarily expended on the runway and during takeoffs. To account for all flight levels in which most contrails are likely to occur, the data were summed for all altitudes above 7 km. The distribution of the sums in Figure 17 reveals the main flight corridors over the US with a primary maximum over the Midwest between Chicago and New York. Other routes to Florida, Atlanta, Dallas, and southern California from the northeast and Midwest are also evident. The geographical variation of contrail occurrence on an annual basis (Figure 18) roughly coincides with the fuel data in Figure 17. For example, maximum contrail frequency occurs over WPAFB in the heart of the Chicago-New York corridor. Offut and Edwards AFBs, which have relatively high frequencies, are under the Chicago-Los Angeles jetways and Eglin, Loring, and Minot AFBs, where contrails are not often observed, are off the main air thoroughfares. Presumably, the discrepancy between the Beale and McClellan AFB contrail frequencies occurs because the latter is closer to the edge of the San Francisco-East Coast airway.

Although the quantity of consumed jet fuel probably increased between 1990 and 1993, the relative pattern of air traffic likely changed little during the interim. Therefore, it should be possible to correlate the 1990 fuel usage with the data in Figure 18 to determine the relationship between the fuel use and contrail occurrence. A surface observer can see high-altitude clouds that are a considerable distance from the surface position. Furthermore, contrails can advect rapidly from their formation location. For example, the climatological mean zonal wind velocities at 300 mb range from ~40 km/hr in July to nearly 100 km/hr in January between 30°N and 45°N (Sadler, 1977). To determine how fuel usage relates to contrail frequency, the effective viewing area for the surface observer's hourly reading must be determined. This area was estimated by correlating the mean annual contrail frequencies to fuel-use averages computed from arrays of 1° boxes. It was assumed that the optimal area corresponds to the array size yielding the greatest correlation coefficient. A 3° box centered at each site produced a linear correlation coefficient, R = 0.73, the maximum correlation between mean fuel use for a square array and persistent contrail frequency. The values of R for 1°, 5°, and 7° boxes are 0.64, 0.62, and 0.41, respectively. Total contrail frequency including both persistent and non-persistent contrails shows a stronger relationship to fuel usage with R = 0.78. Scatterplots and linear regression fits forced through the origin are shown in Figure 19 for the 3°-box fuel averages and total and persistent contrail frequencies determined without indeterminate data. According to this fit, the mean annual total and persistent contrail frequencies are

$$c_t = 0.00176\, f, \quad (1)$$

and

$$c_p = 0.00127\, f, \quad (2)$$

respectively, where f is the mean fuel use above 7 km of the nine 1° boxes centered over a given location. Fuel consumption is given in 10^6 lbs yr^{-1}. While these correlation demonstrate the obvious, that the likelihood of observing a contrail increases as the number of planes at altitude increases, it also quantifies, for the first time, the relationship between aircraft fuel usage and contrail frequency. Moreover, it shows that over the US, fuel expenditure can account for 61 percent (R^2) of the variance in mean annual persistent contrail occurrence and that contrail occurrence will increase as air traffic volume expands.

Using the mean 3° regional US fuel usage above 7 km, 4.8 x 10^6 lbs yr^{-1}, in Eq. (1) yields a mean occurrence frequency of 0.085 for the country as a whole. This result suggests that, on average, an observer situated at a random location and time in the US will have an 8.5 percent chance of seeing a contrail if the sky is not totally obscured. Before the commercial jet age began in earnest during the 1960's, contrails were a rare sight. In some regions like the midwestern US, especially during winter, the likelihood of observing a contrail is on the order of 40 percent, an almost every other day occurrence.

Meteorological Conditions

Fuel use cannot account for all of the variability in contrail occurrence. Most of the remaining variance is probably due to the diverse temperature and relative humidity *RH* conditions at flight level, although engine and fuel type as well as the operating conditions also influence contrail formation. While a detailed examination of the meteorological conditions affecting contrail occurrence is beyond the scope of this study, monthly averages of certain parameters are examined to demonstrate how atmospheric profiles may affect the contrail frequencies in this dataset.

Because of the typically low relative humidities in the stratosphere, a plane is unlikely to produce a significant contrail if it flies above the tropopause. Figure 20 shows the variation of mean tropopause altitude z_p with observing site for 3 months. During January 1994, z_p varies from 9.6 km in Maine to over 12 km in Texas. Most of the heights are between 10.5 and 11.5 km. The tropopause height generally increases during April 1994 to between 10.8 and 14 km. During July 1993, the range is 10.8 to 16 km. If 10.5 km is assumed to be the average flight level, then most of the air traffic over the US takes place in the troposphere, even during much of the winter. The two exceptions are Loring AFB and Minot AFB where z_p = 9.6 and 10.1 km, respectively, during January 1994. As seen in Appendix A, the maximum contrail frequencies primarily occur during the winter and early spring months except over these two sites. The maximum for Loring occurs during May and June, while the peak contrail frequency over Minot is seen during October. The lowered tropopause during winter in northern latitudes is also the likely source for the southward displacement of the contrail maximum during winter over the North Atlantic air traffic routes reported by Bakan et al. (1994).

The mean temperatures T_f at the average flight level provide further explanation of the seasonal variability. In Figure 21, T_f increases from January through July at all locations. During July 1993, T_f is greater than 225 K over all sites but Fairchild AFB in Washington. The mean flight level temperatures are 225 K or less during January 1994. According to Hanson and Hanson (1995), contrail formation at 10.5 km or near 250 mb requires temperatures lower than 226 K (-47°C) for RH less than 100 percent. As the temperature decreases, the relative humidity required for contrail formation also decreases. Thus, the probability for contrail occurrence increases as the temperature drops. The winter maximum in contrail frequency, therefore, is primarily due to the colder temperatures at flight level. Contrails were observed over all of the sites during July 1993 when T_f generally exceeded 225 K. The non-zero contrail occurrence may be attributed to variations in T_f over the month or to contrails occurring at higher levels. The variability in T_f can probably account for July contrails over the northern sites but not over the southern locations. The Hanson and Hanson (1995) calculations indicate that contrails can form at temperatures as warm as 244 K but only in very moist conditions at much lower altitudes. For example, they found that the critical temperature for contrail formation at 500 mb for a low bypass engine is -40°C at RH = 70 percent with respect to liquid water. Thus, contrails may be formed when jet aircraft fly through moist layers at lower altitudes. However, this phenomenon is not likely to occur during the summer. As seen in Figure 16, there is still considerable air traffic at 12 km. These flights at the higher altitudes (colder temperatures) are probably the source of contrail development over the southern sites during July.

Figure 22 shows the mean relative humidities for each site during the 3 months considered earlier. These values generally range between 33 and 42 percent. July appears to be the driest month overall. The increased RH during January and April is not much greater than the July values, however. Thus, these humidity values are not likely to explain much of the variation in contrail occurrence. Despite this apparent lack of humidity dependence, the frequent co-occurrence of contrails and cirrus is a clear indication that contrails form more often when water vapor is more abundant. The absence of an association between RH and contrail occurrence may reflect the oft expressed need for better measurements of humidity in the upper troposphere (e.g., Schumann, 1995).

Earlier Contrail Observations

As noted earlier, contrail observations over the US have been limited to either a small area or time period except for the satellite study by DeGrand et al. (1990). That brief report discussed the occurrence frequencies and found the greatest density over southern California, central Arizona and New Mexico, and over the Midwest. The current results are consistent with that finding except for the southwestern US relative maximum. This discrepancy may be due to a change in flight patterns, the location of Luke AFB (the only southwestern site) south of the primary flight corridors (Figures 1 and 17), or to differences in the interpretation of persistent and non-persistent contrails. It is unlikely that flight patterns have changed considerably since 1978 and, although this site is not immediately underneath the flight corridors, a considerable amount of fuel is expended within 150 km of Luke AFB (see Figures 1 and 17) resulting in the potential for many advected contrails. If non-persistent contrails are included for Luke AFB, the overall frequency of occurrence increases from 5.4 percent to 14.6 percent, a value more consistent with the fuel usage around Luke and close to values obtained for the nearest contrail site, Edwards AFB. Given that the frequency of non-persistent contrails over Luke AFB is more than twice that of any other base and that satellite observers generally only see persistent contrails, it is possible that the observers at Luke AFB used a different criterion for determining contrail persistence than those at the other sites. Nevertheless, if the non-persistent contrails are included in the average, then the current results are qualitatively consistent with the earlier satellite study.

DeGrand et al. (1990) also found a seasonal variation that differs from the present results. Their maximum frequency occurs during October with a minimum during July. In Figure 8, the maximum contrail frequency occurs during February or March regardless of consideration of indeterminate data. A minor, statistically insignificant, secondary peak is evident during October (Figure 8a) in the raw data but it is less than both of the January and April values. If indeterminate data are not considered, October ranks seventh for contrail occurrence. This difference from the DeGrand et al. (1990) results is difficult to reconcile. It is possible, but unlikely, that the difference is due to sampling. Although only an average of 13 months of data was used for the present study, the seasonal results are consistent for almost all sites over the US and with the meteorological trends. Whether this seasonal cycle is typical on a climatological scale is a question that can only be addressed with further observations.

The discrepancy between the DeGrand et al. (1990) and the current results, however, may arise from the differing viewing perspectives of the satellite and surface observers. The surface observer can easily recognize a thin contrail shortly after its formation. If it undergoes significant growth, however, it may be interpreted as a cirrus by a surface observer but could still be recognized as a contrail in infrared satellite imagery, especially against a warm backdrop, because of its linear characteristics. Thus, advecting contrails that have had time to grow may often be identified as cirrus clouds by a surface observer while counted as contrails in infrared image analysis. It is possible that much of the excess cirrus cloudiness detected in the autumn surface observations relative to climatology (Figure 13b) may be contrail cirrus rather than natural cirrus. Such an interpretation would be compatible with the results of Angell (1990) who found that cloudiness increases over the US were greatest during autumn and were most likely due to thin cirrus.

Conversely, contrails may be easily distinguished against a blue sky from the surface but may be difficult to detect in morning and evening satellite imagery when the background is cold. Because contrails are optically thin, they provide minimal contrast in infrared imagery unless the background is significantly warmer than the cloud. Bispectral brightness temperature difference techniques (e.g., Lee, 1989) rely more on the contrail's small particle size and should be more effective for detecting contrails in low contrast conditions. Because the Degrand et al. (1990) data were limited to a single infrared channel, it is probable that many contrails were not detected during winter and early spring when the background is significantly colder than it is during summer and autumn. This contrast problem would be exacerbated by the lack of DMSP satellite data during the afternoon when the contrast between clouds and the surface is greatest during all seasons. Furthermore, because the satellite resolution is between 1 and 8 km, only the largest persistent contrails can be detected. It is possible that the differences in the seasonal cycle of contrails are due to a combination of viewing perspective and contrail growth. Coordinated surface and satellite analyses would be needed to better reconcile the differences.

Diurnal Variability

Because the observations were limited to sunlit hours , the diurnal variations are incomplete and the mean frequencies may be in error. Commercial aircraft frequently operate at night over the US, especially before local midnight and after 0600 LT. Contrails from early morning flights will be missed in the observations during the winter months, in particular. Inclusion of nocturnal observations could change the results for the diurnal statistics and would affect the overall mean frequencies. Because air traffic is generally heavier during the daytime, the times of maximum contrail occurrence found here are probably accurate for most of the sites. The minimum hourly frequencies, however, would probably be lower if 24-hour observations were used. For the same reasons, the mean contrail frequencies would be smaller than the current daytime values.

The diurnal maxima seen in Figure 11 may reflect, to some extent, the timing of flights over the US. Contrails observed over a particular site are probably due to flights that originated or terminated at least one half hour from the site because of the time needed to reach or descend from cruising altitude. Primary morning maxima over the east (75-85°W) suggest that most flights commence early in the day before 0800 - 0900 LT. The secondary afternoon maxima are probably the result of later originating and the arrival of eastbound flights. A similar breakdown of flights occurs over the west coast with a mixture of afternoon and primary maxima. The number of long distance flights in either direction plus the north-south traffic would shift both the primary and secondary peaks to the late morning and late afternoon over the center of the country. The exception to this general pattern is Loring AFB which is primarily affected by US-European air traffic. Much of the eastbound traffic originates during the late afternoon and early evening for morning arrival while the westbound flights arrive earlier in the day. While the connection between flight times and contrail occurrence is complex and cannot be fully explained here, the observations are consistent with the general constraints imposed by commercial air traffic. A complementary analysis of satellite data covering the entire day would help complete the depiction of contrail diurnal variability.

Other Considerations

Relying on the interpretation of surface observers, these data are subject to some errors based on the judgment of a particular observer. Distinguishing a contrail from a natural cloud can be difficult a short time after the contrail's formation. As a consequence, some bias toward underestimation of contrail frequency is probable because only those contrails that can be confidently identified will be included in the observations. It is unlikely that any older contrails missed in the statistics will be offset by cirrus clouds mistaken as contrails. The threshold between the persistent and non-persistent contrails is also subjective to some degree and will result in uncertainty in the actual ratio of persistent to non-persistent contrails. It was noted earlier that the high incidence of non-persistent contrails over Luke AFB compared to other sites may be the result of different criteria used for determining persistence.

The viewing conditions can also influence the detection of contrails. Observations represent the conditions at one instant. Therefore, the line of sight to contrails may be blocked at a given time by scattered or broken cloud conditions. In overcast situations, this effect is recognized in the indeterminate category, but it is possible that contrails can remain unobserved in other circumstances. Although Figure 15 indicates that persistent contrails were most often seen during mostly cloudy conditions, it is possible that the actual frequency is even greater due to line-of-sight obstruction. This effect would also cause additional underestimation of the true contrail frequency. In this analysis, it was assumed that the frequency in the indeterminate cases is the same as in the determinate viewing conditions. This assumption has not been tested yet. Proper accounting for the cases in which the contrails are potentially obscured will require analyses of satellite data coincident with the surface observations.

Concluding Remarks

This paper provides the most complete inventory of contrail frequencies over the US to date. It is just the first step, however, in assessing the impact of aircraft condensation trails on climate. Because only 1 year of observations was available, it is not possible to unequivocally conclude that this dataset is a reliable climatology of US contrails. Data from other years are needed to develop such a climatological picture. Much additional information is also required to confidently estimate the radiative effects of contrails. Statistics regarding the lifetimes, areal coverage, optical properties, and advection of contrails and contrail cirrus are essential to properly characterize changes in the mean radiation fields. Assessment of climate change due to increasing air traffic appears feasible, however, because of the strong relationship found between fuel usage and contrail occurrence and the consistency between seasonal meteorology and contrails. The contrail dataset presented here can be exploited to refine the relationships between contrails and fuel consumption and meteorology. Correlations between temperature and humidity from soundings coincident with hourly contrail observations will be critical to empirically quantify the trends found here. A more detailed seasonal analysis of fuel use and contrail frequency could be useful for simulating contrail occurrence over a given location in the US. With supplemental nocturnal data, it may be possible to realistically simulate the diurnal cycle as well. The hourly observations can also serve as validation data for coincident satellite retrievals of contrail occurrence. Combination of satellite retrievals and these surface observations will be required to completely depict the entire diurnal cycle.

Contrails have become a prevalent feature of American skies. The relationships established here indicate that they will become even more common in the future as airline service expands. Because contrails add directly to cloud cover, they will affect the radiation budget at some magnitude. Even if the impact is determined to be small on a global scale, the local effects may still be substantial. Thus, it is important to determine the relationships between contrail frequency and changes in cloud cover. This surface analysis of contrails should also be repeated in a few years when air traffic has increased significantly to detect any changes in contrail occurrence and to test any prognostication schemes developed from this dataset. Commercial air traffic is growing worldwide with the potential for an increase in contrails over many areas outside of the US. To fully assess contrails on a global scale, their detection and reporting should be made a routine part of standard meteorological observations. Because they are a distinct type of cloud, they could easily be included as part of the cloud type codes currently used in the global meteorological observing system. An accurate evaluation of the climatic impact of contrails will require an effort that combines surface and satellite observing systems.

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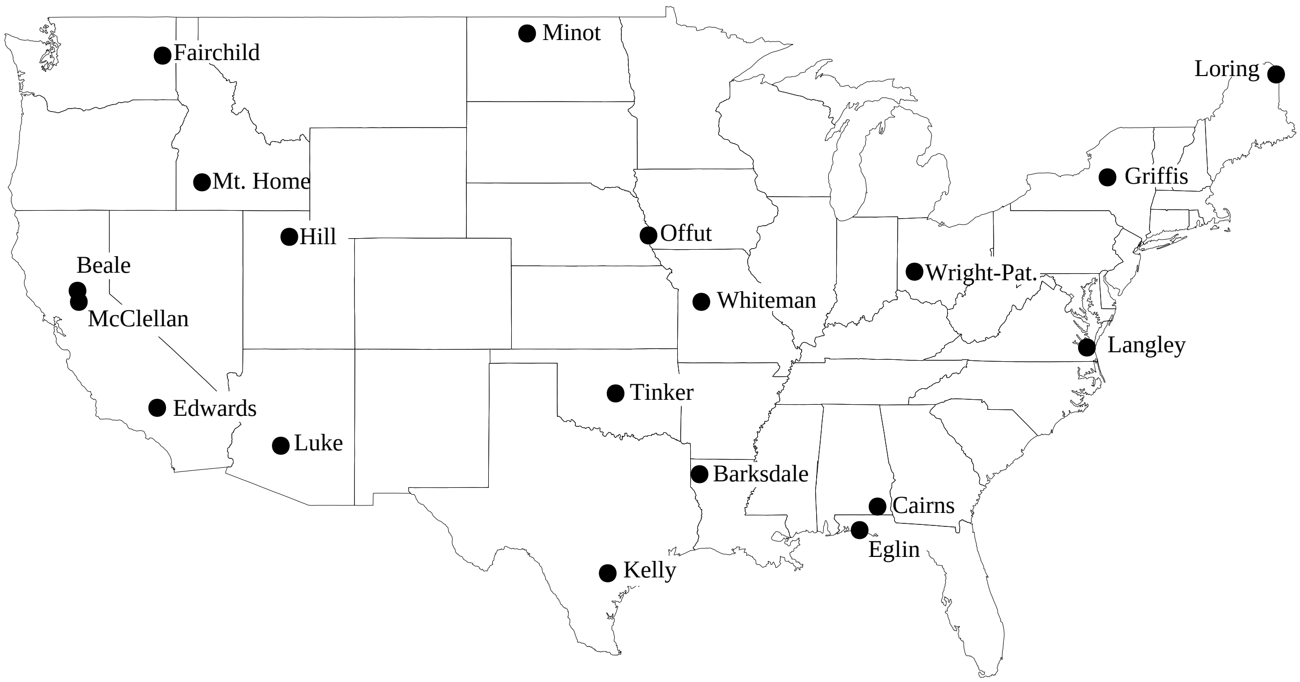


Figure 1. Contrail observation network, comprised of 19 U.S. Air Force Bases and Army Air Facilities.

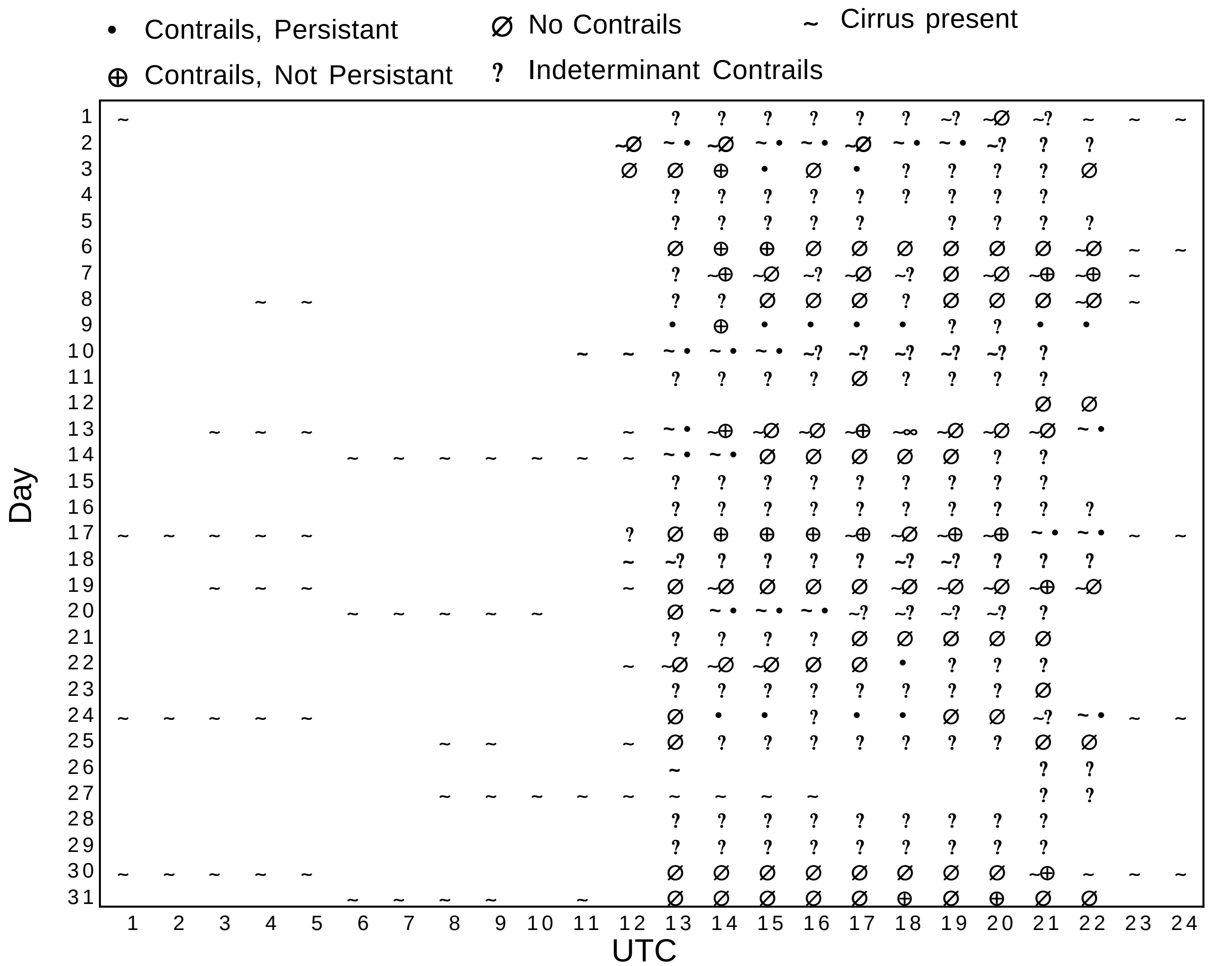
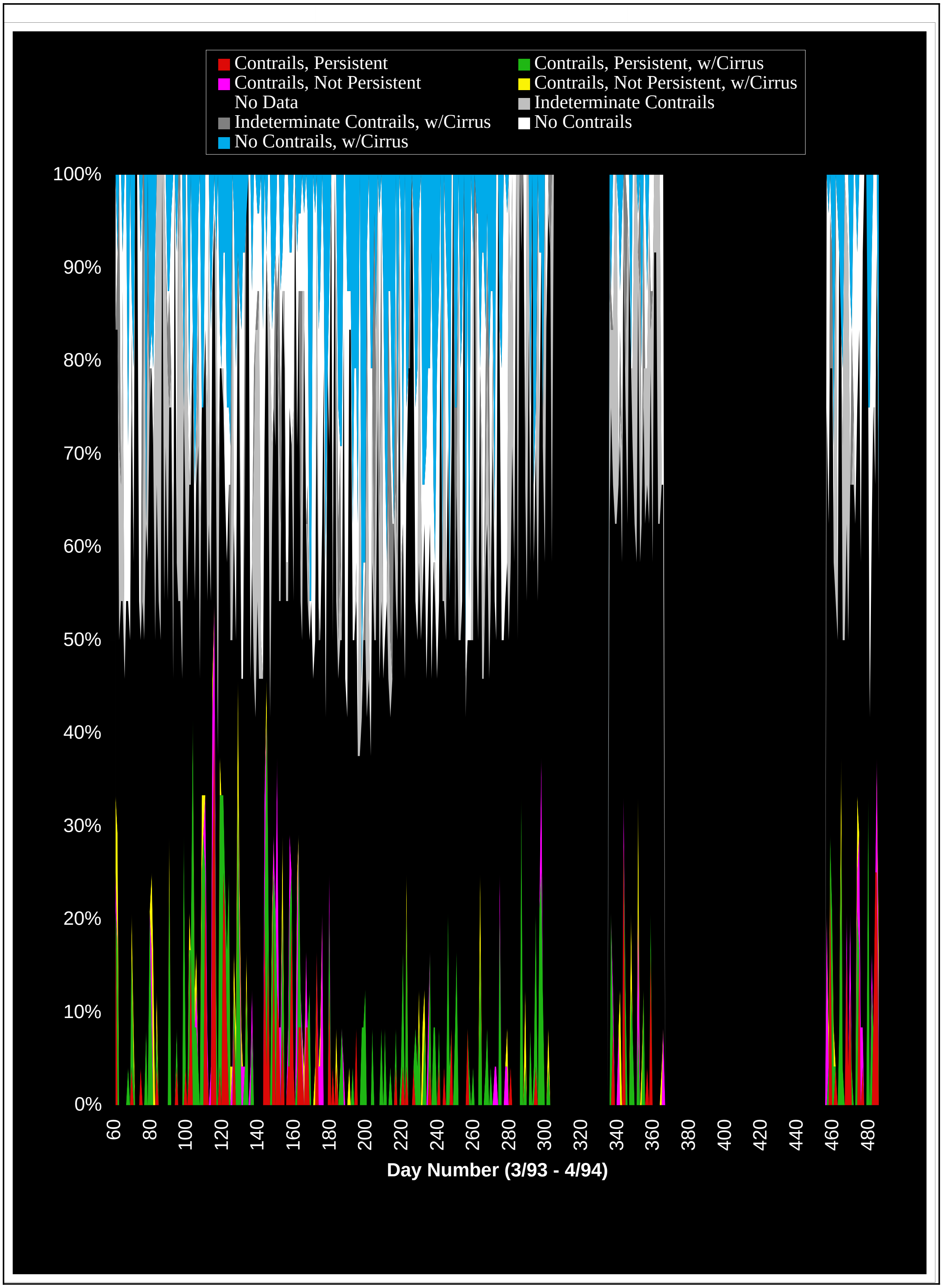


Figure 2. Coded summary of Langley AFB December 1993 contrail and cirrus observations.


Contraits, Persistent
Contrails, Persistent, w/Cirrus
Contrails, Not Persistent
Contrails, Not Persistent, w/Cirrus
No Data
Indeterminate Contrails
Indeterminate Contrails, w/Cirrus
No Contrails
No Contrails, w/Cirrus
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
60
80
100
120
140
160
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Day Number (3/93 - 4/94)

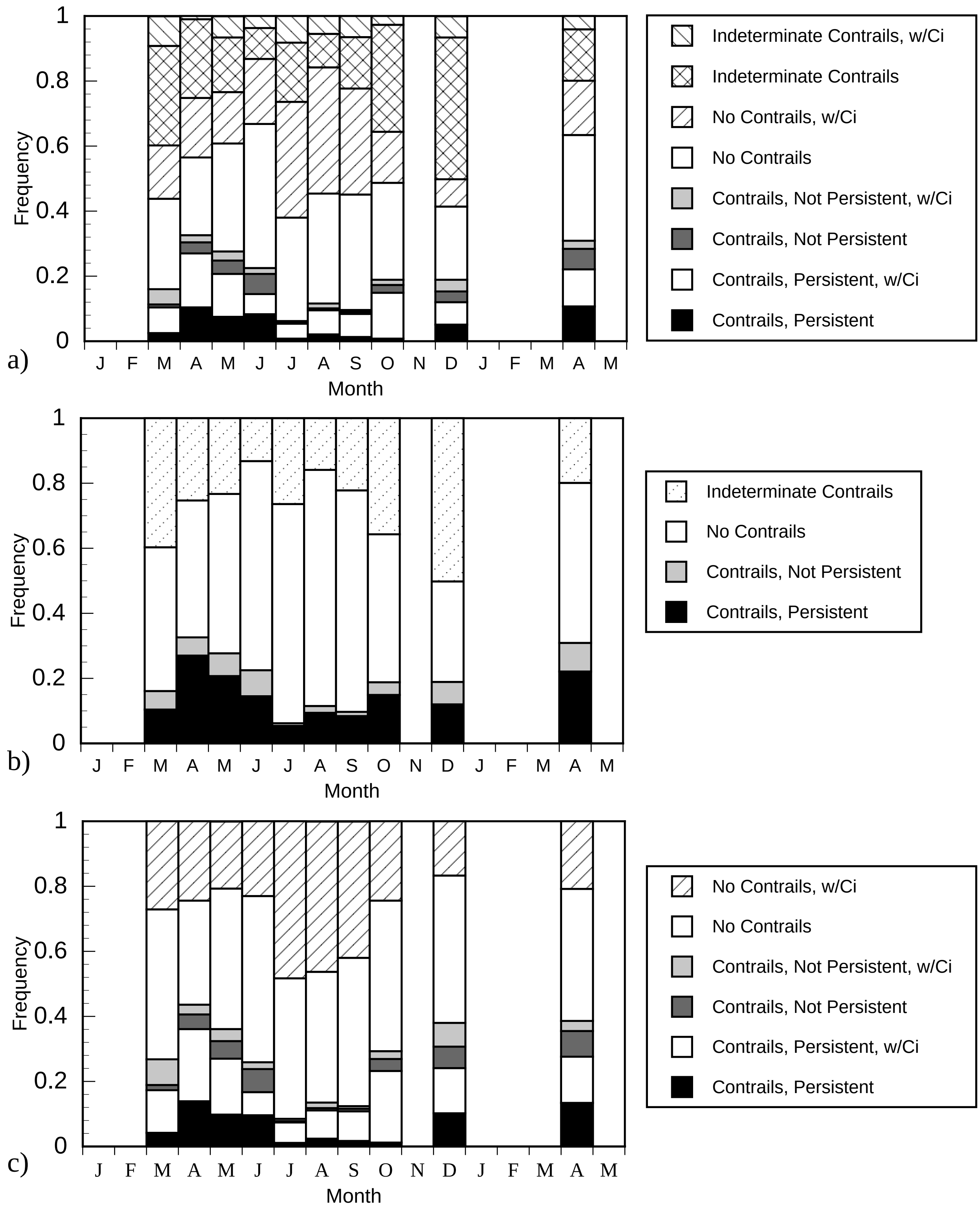


Figure 4. Summary of monthly observations for Langley AFB, Virginia from January 93 to May 94: (a) relative frequency of contrails and cirrus, (b) relative frequency and persistence of contrails, and (c) relative frequency of contrails and cirrus with indeterminate data removed.

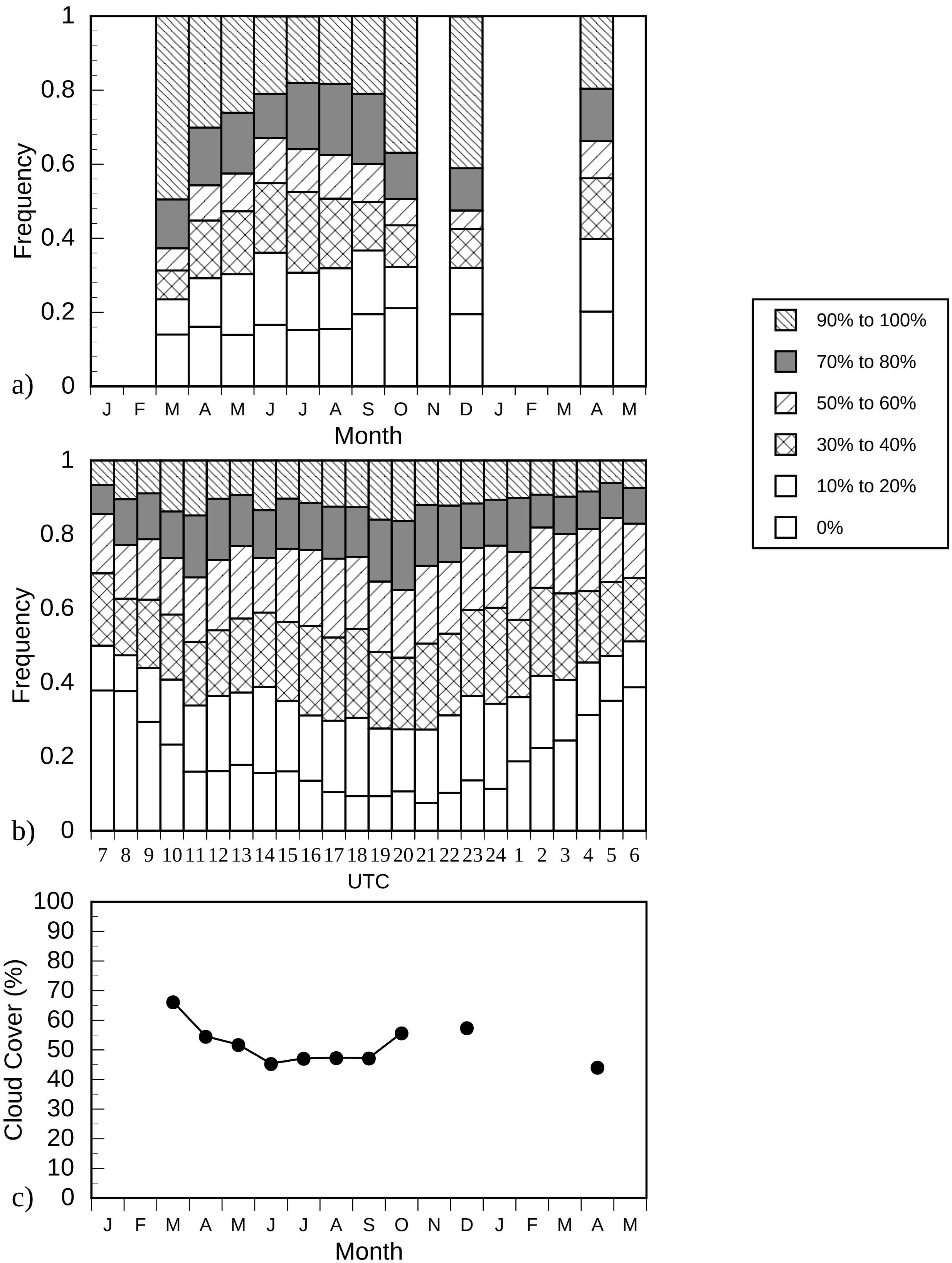


Figure 5. Summary of cloud cover for Langley AFB, Virginia from January 93 to May 94: (a) relative frequency of cloud cover, (b) diurnal cycle of cloud cover relative frequency centered at local noon, and (c) monthly mean cloud cover.

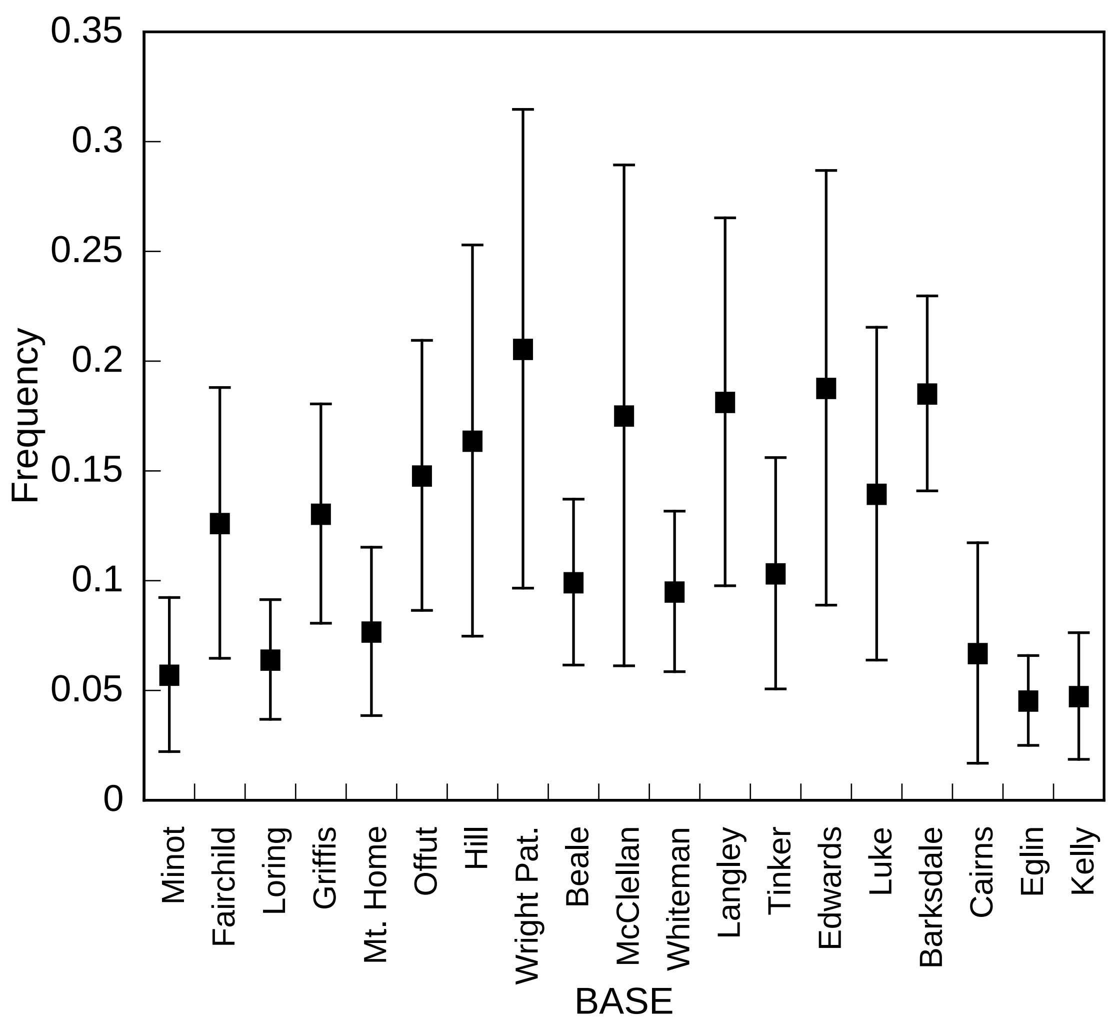


Figure 6. Mean and standard deviations of combined persistent and non-persistent monthly contrail frequencies, sites ordered North to South according to lattitude.

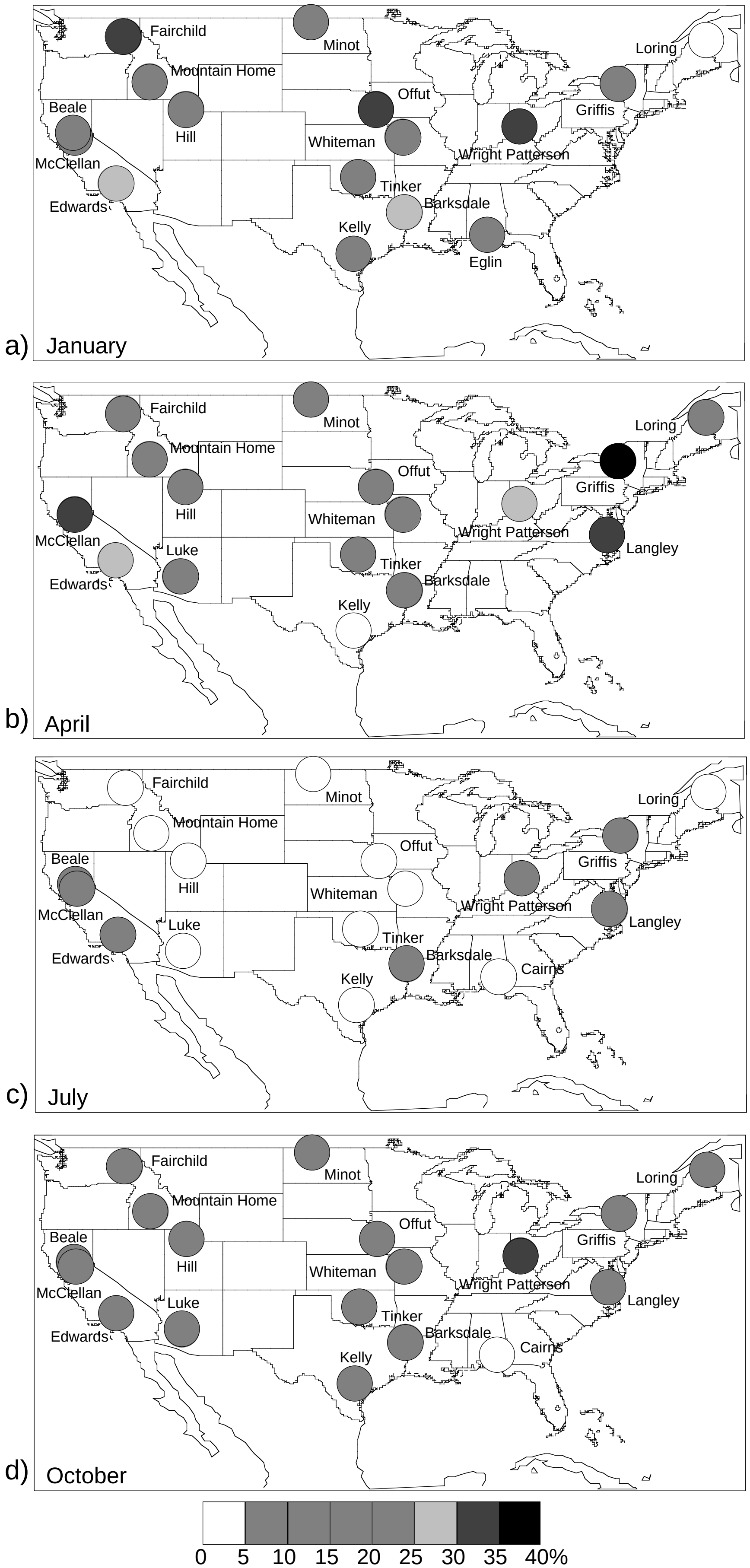
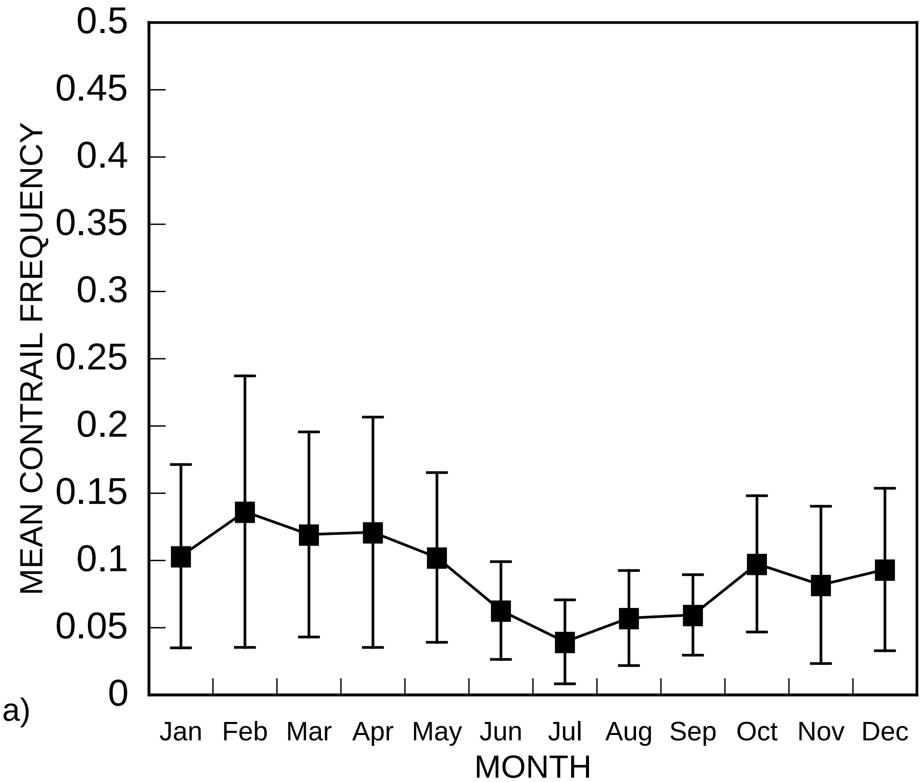
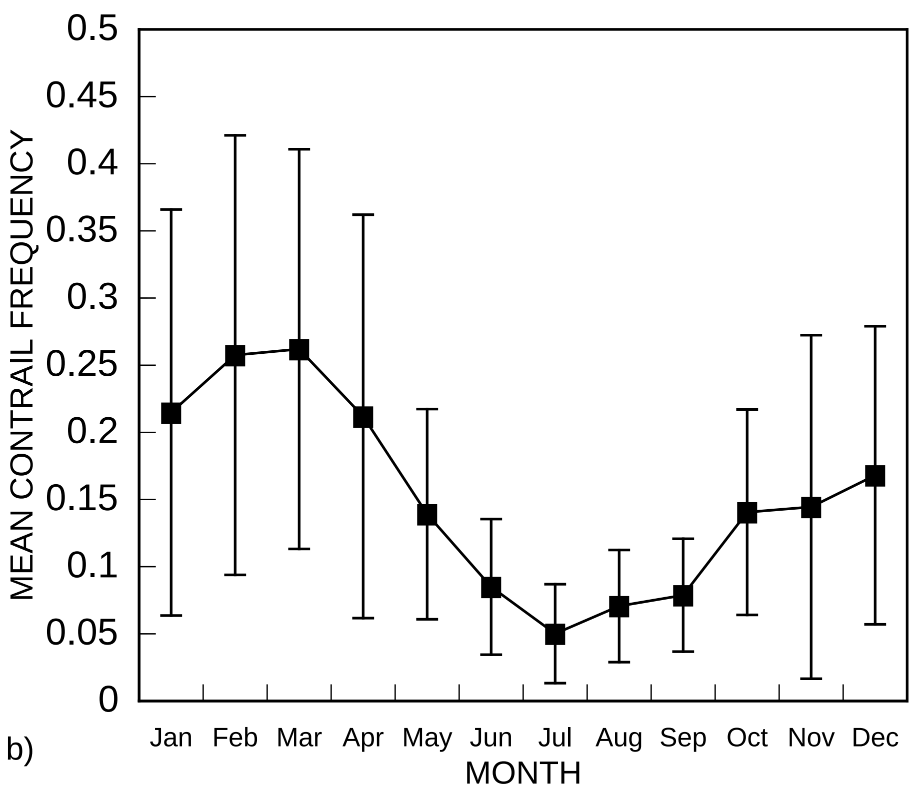


Figure 7. Comparison of persistent contrail frequency with indeterminate data excluded for several months. a) January. b) April. c) July. d) October.



a)



b)

Figure 8. Monthly mean persistent contrail frequency for 19 sites. Bars indicate standard deviations: a) All daytime data. b) Indeterminate data excluded.

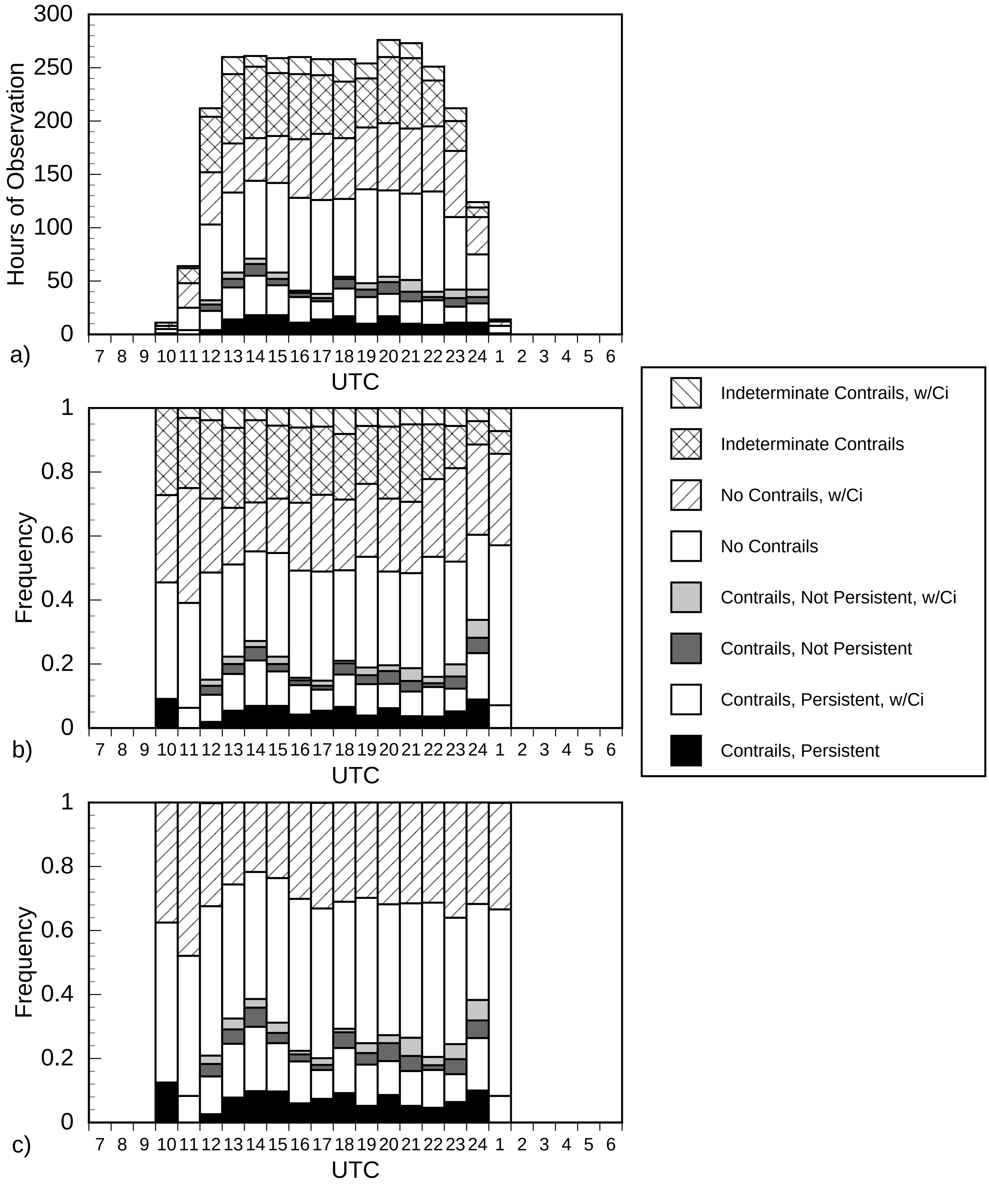


Figure 9. Summary of hourly contrail and cirrus observations from Langley AFB, Virginia, centered at local noon: (a) number of observations, (b) relative frequency of occurrence, and (c) relative frequency of occurrence with indeterminate data removed.

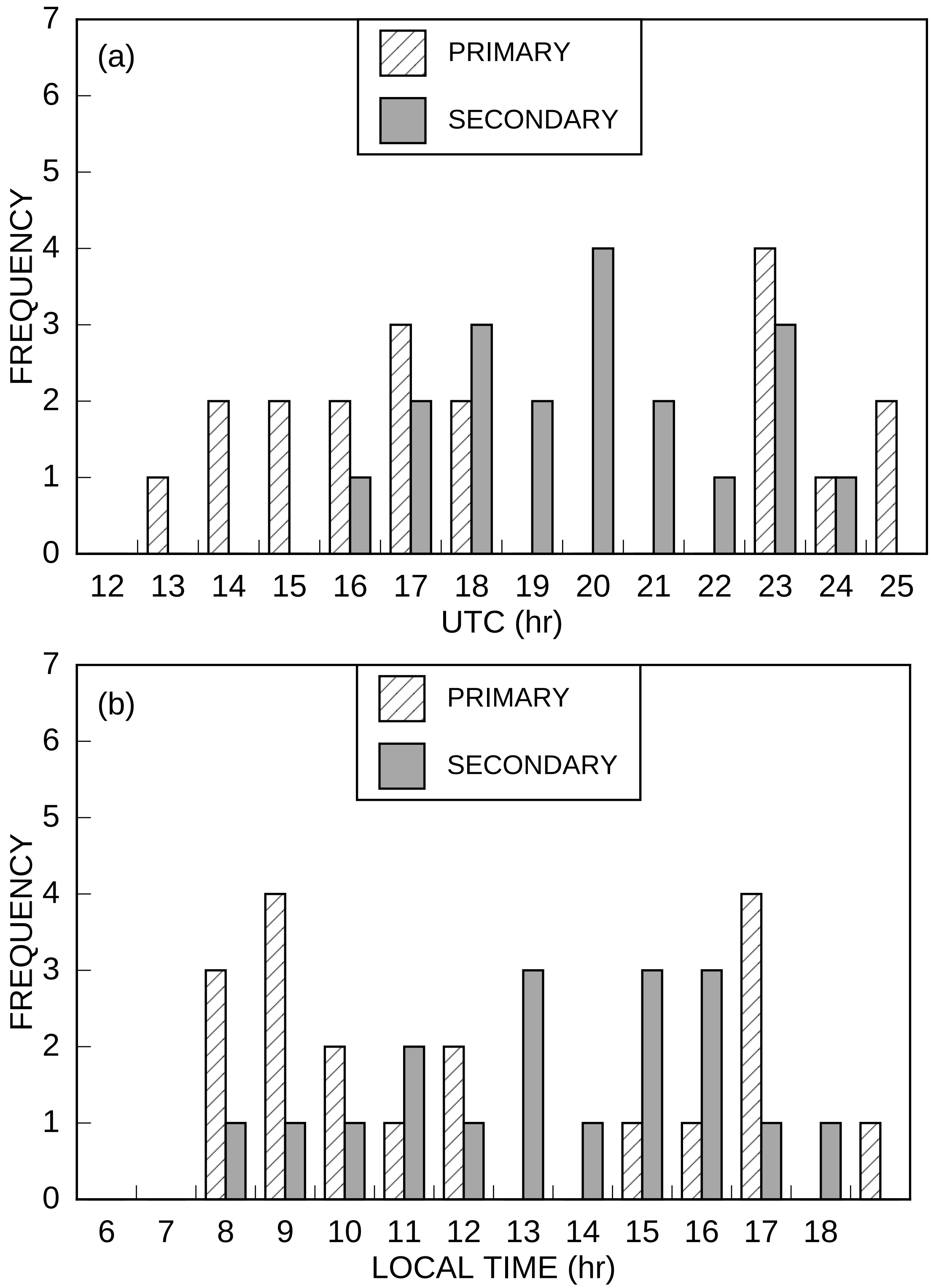


Figure 10. Times of maximum contrail occurrence for the 19 study sites.

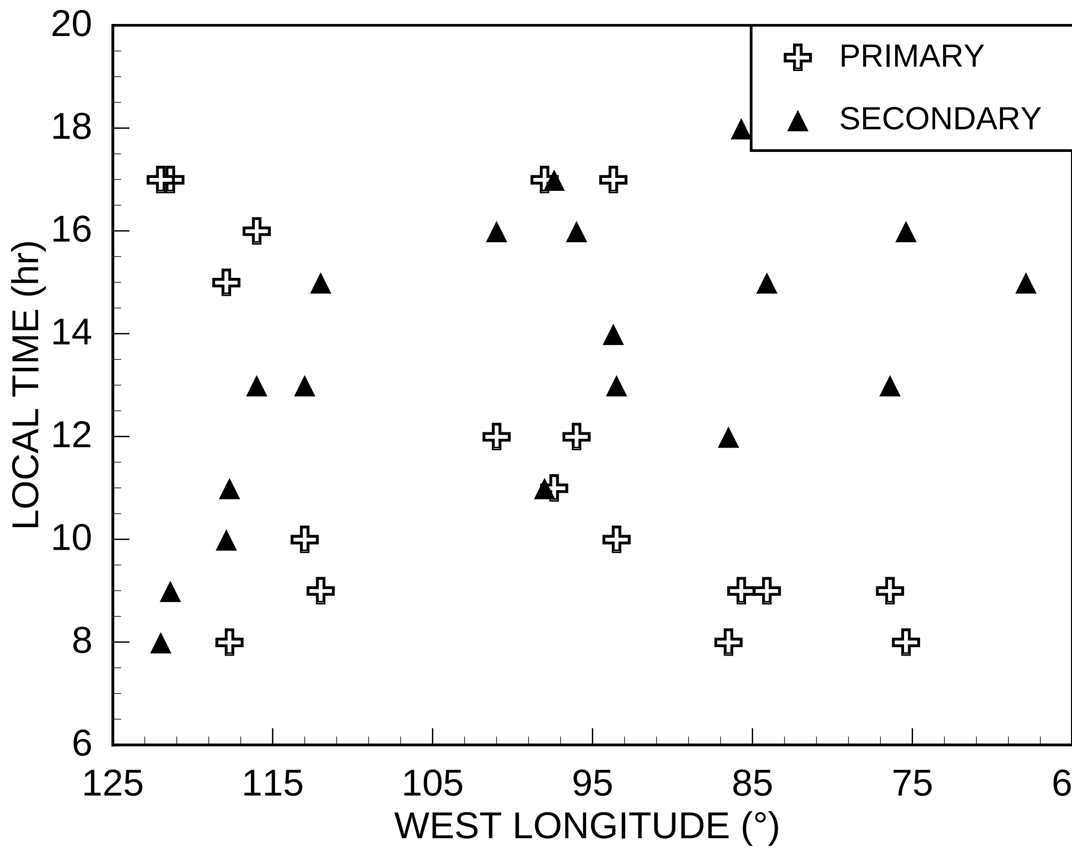


Figure 11. Longitudinal dependence of times of maximum contrail occurrence.

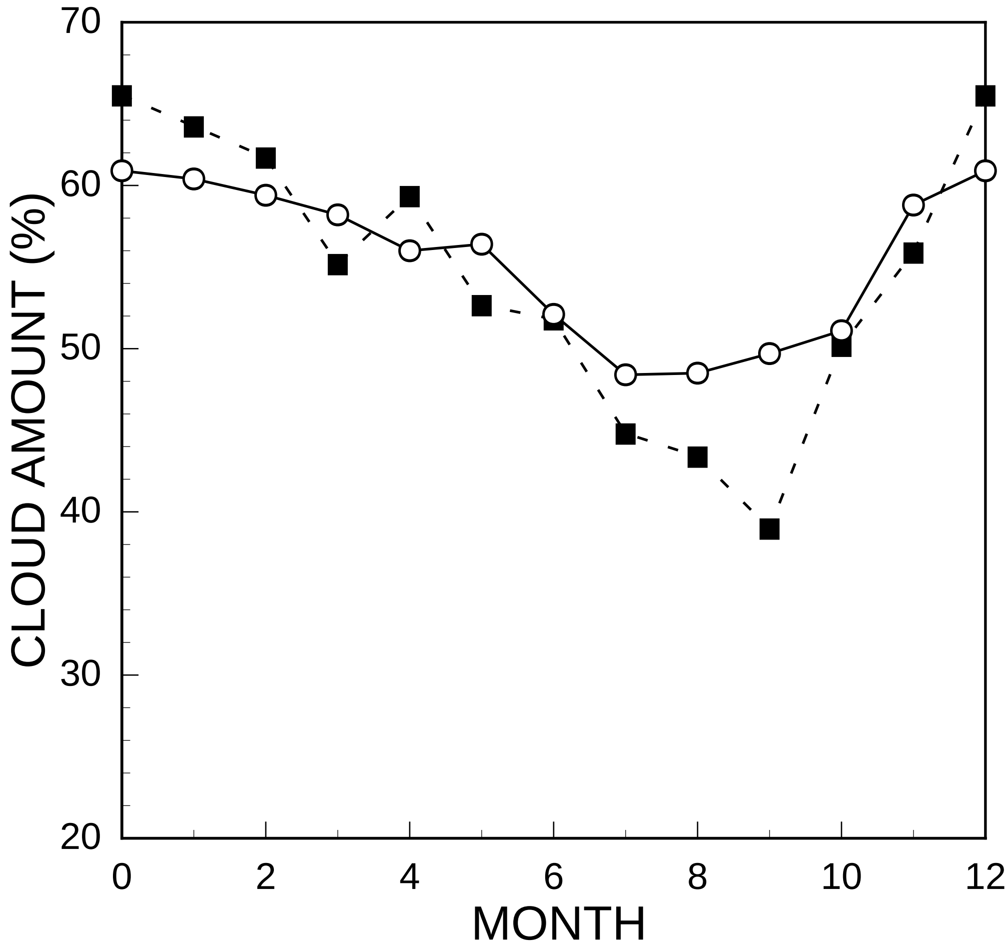


Fig. 12. Comparison of U.S. climatological average and contrail-data monthly mean cloud cover.

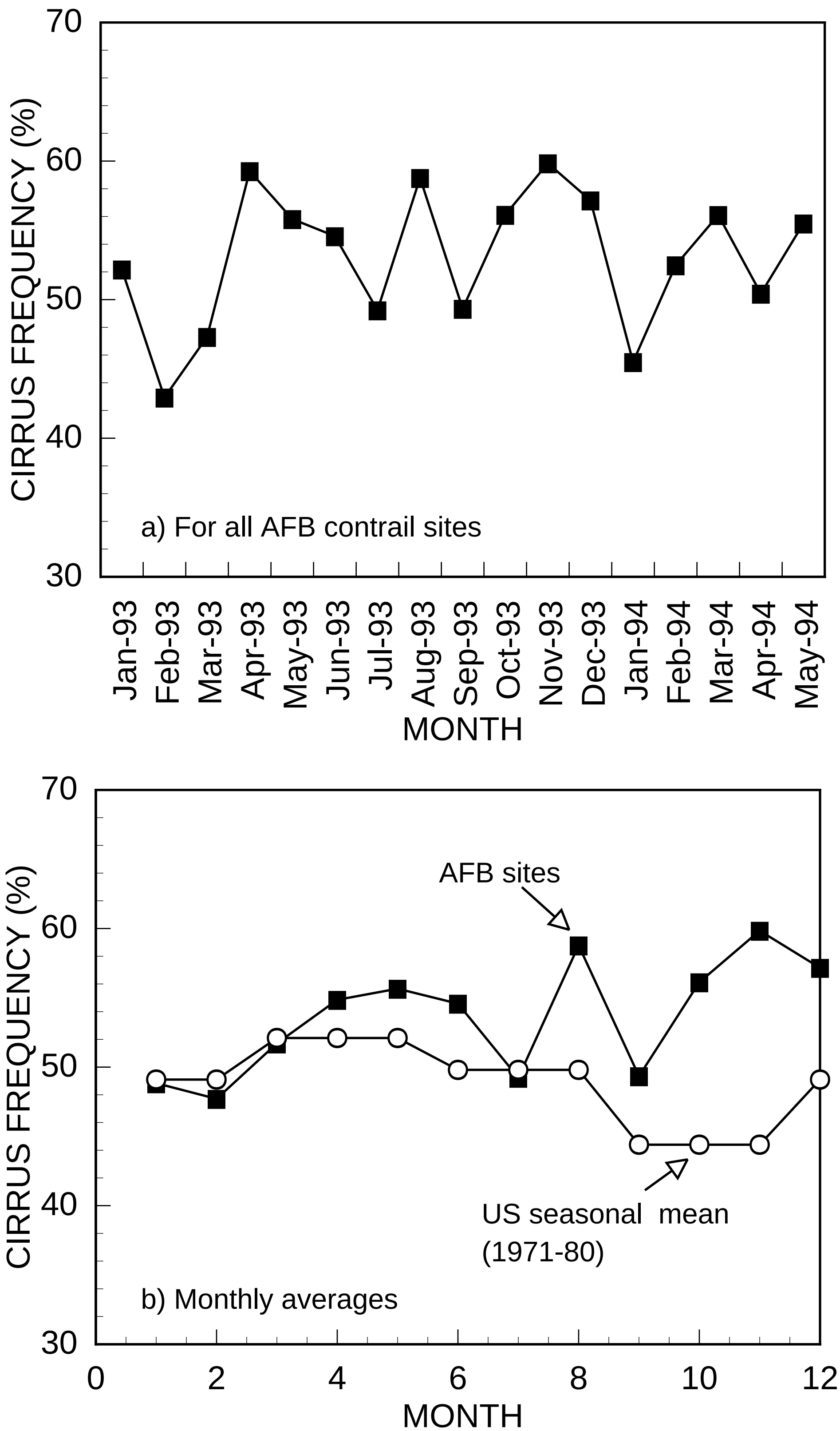


Figure 13. Frequency of cirrus occurrence over the contrail-data sites and the U.S. climatological mean.

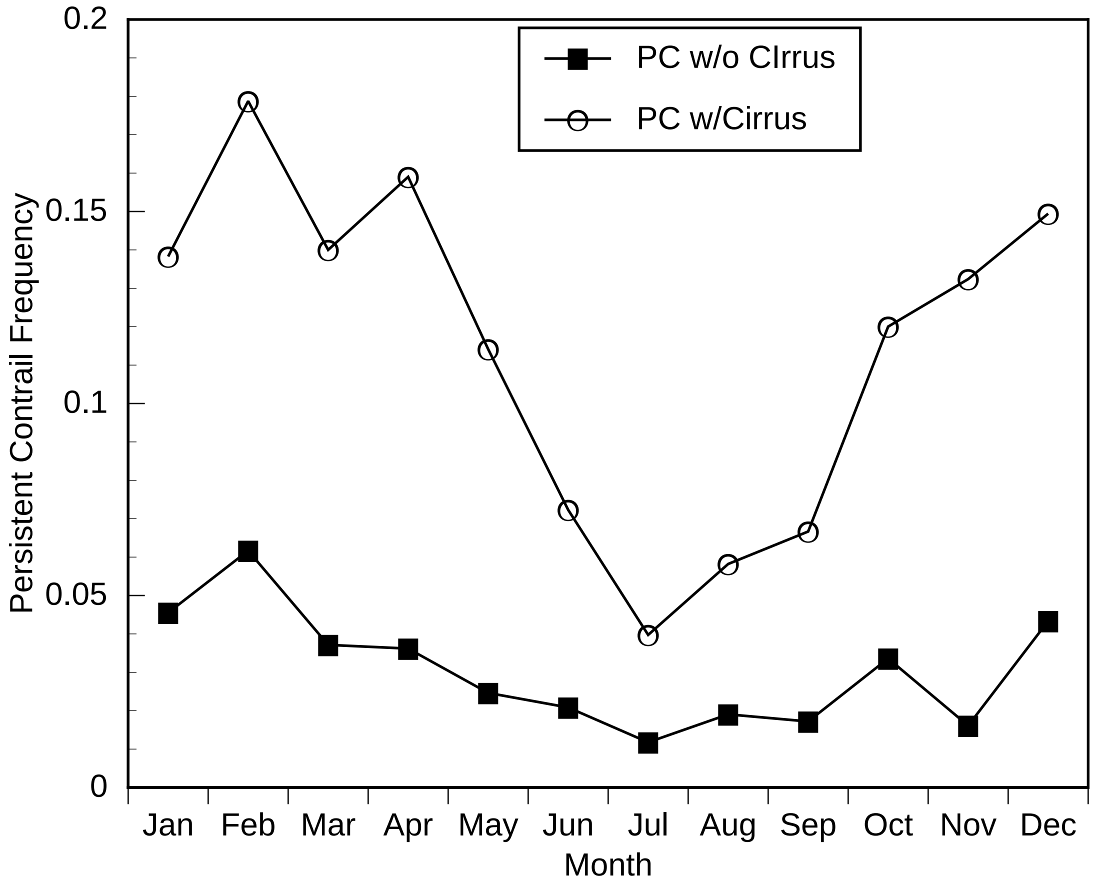
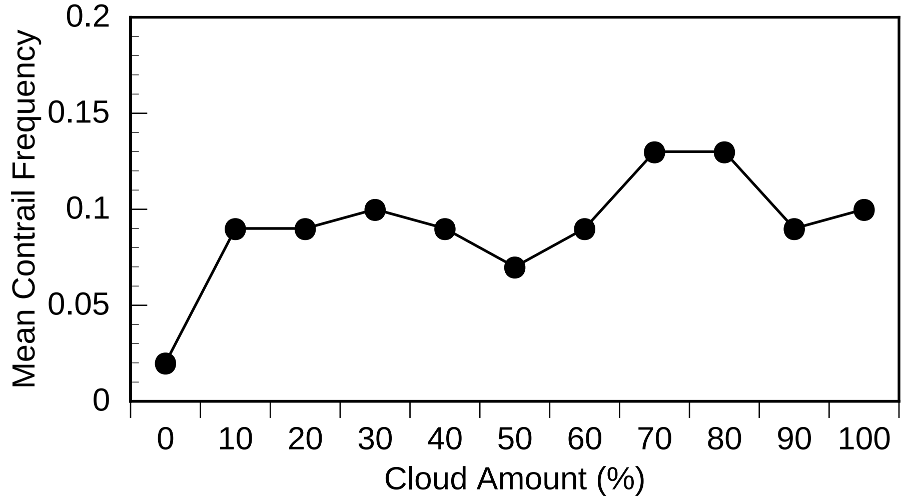
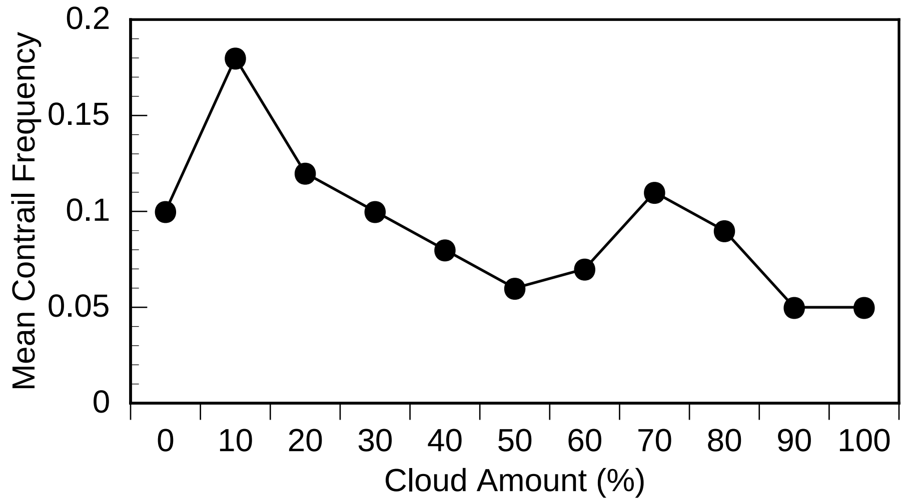


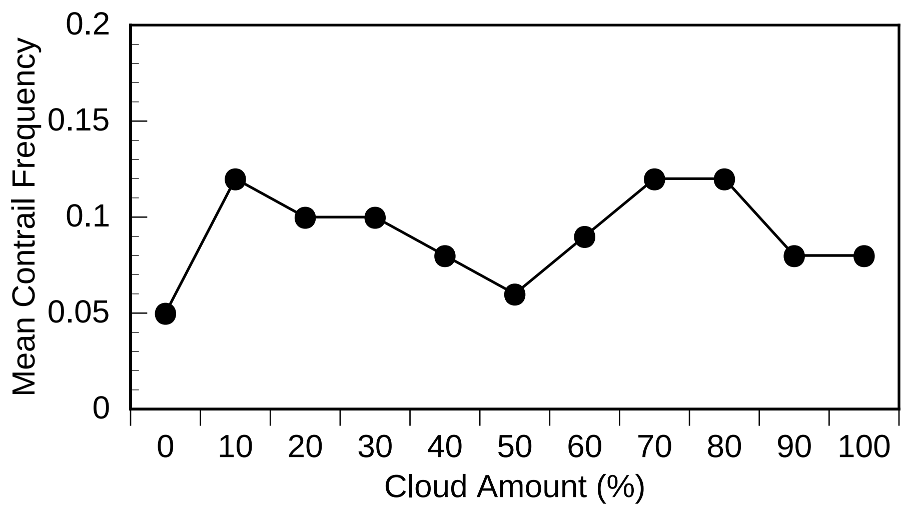
Figure 14. Monthly mean persistent contrail frequency with and without cirrus for all 19 surface sites.



a)



b)



c)

Figure 15. Contrail frequency as a function of cloud amount: a) Persistent contrails only. b) Non-persistent contrails. c) All contrails.

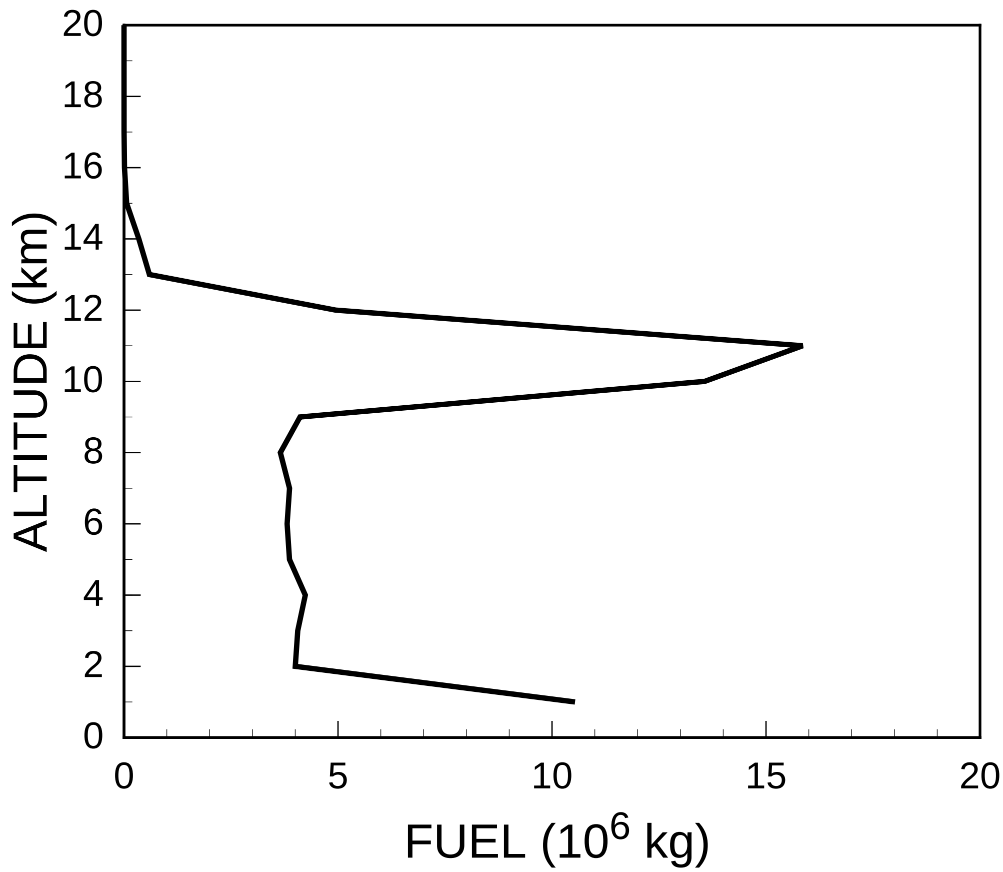


Fig. 16. Vertical distribution of annual mean fuel use for 3° latitude-longitude boxes centered over the 19 U.S. contrail observation sites based on May 1990 data from Baughcum et al. (1993).

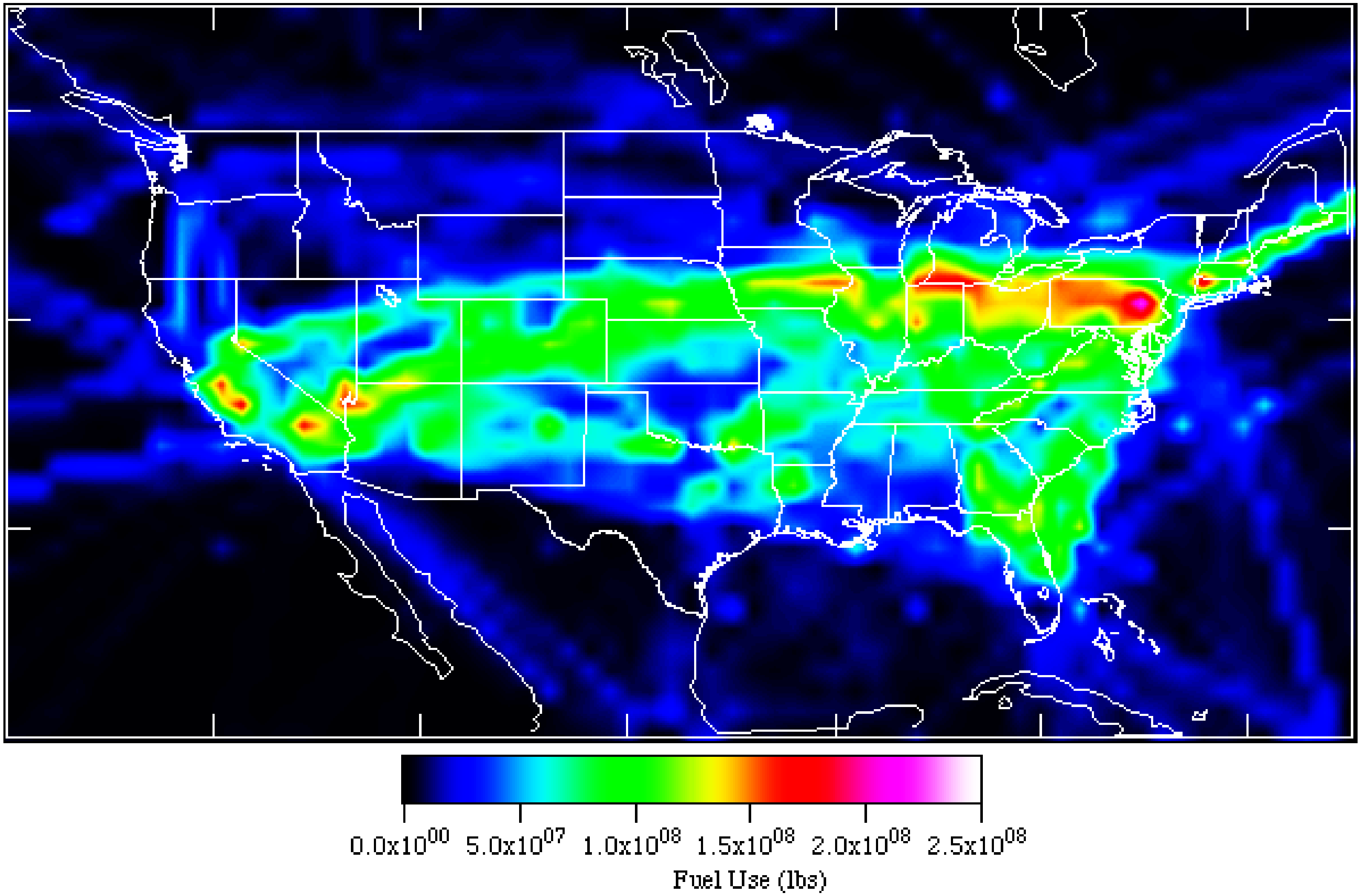


Figure 17. Fuel use estimate for 1990 for altitudes above 7 km.

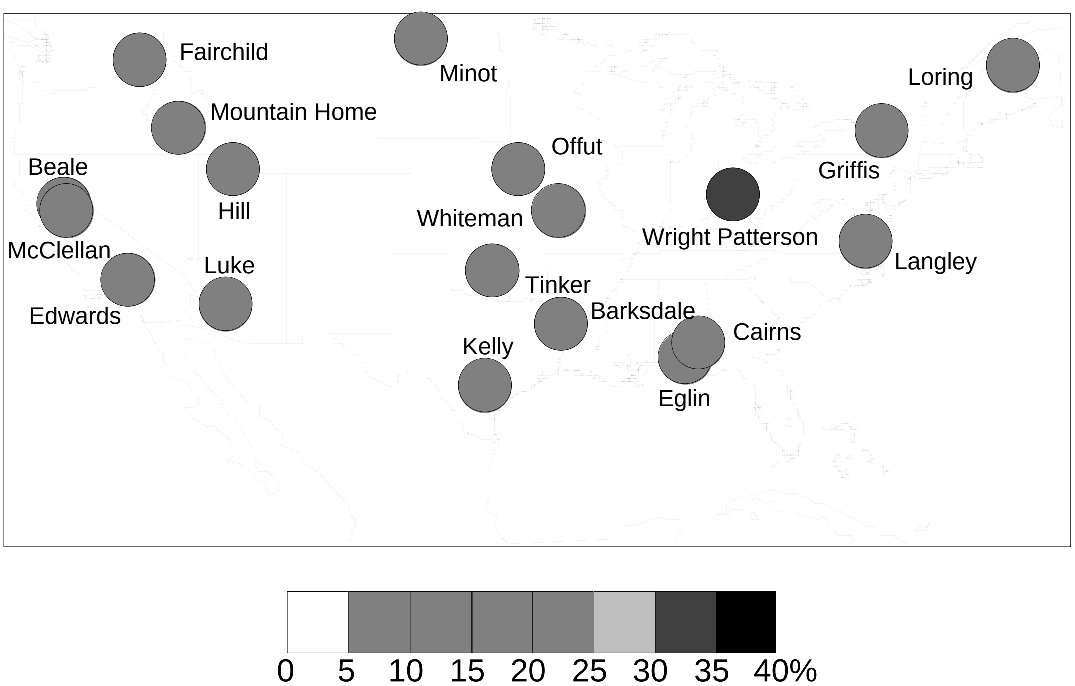


Figure 18. Comparison of annual mean persistent contrail frequency excluding indeterminate data for 19 surface observation sites.

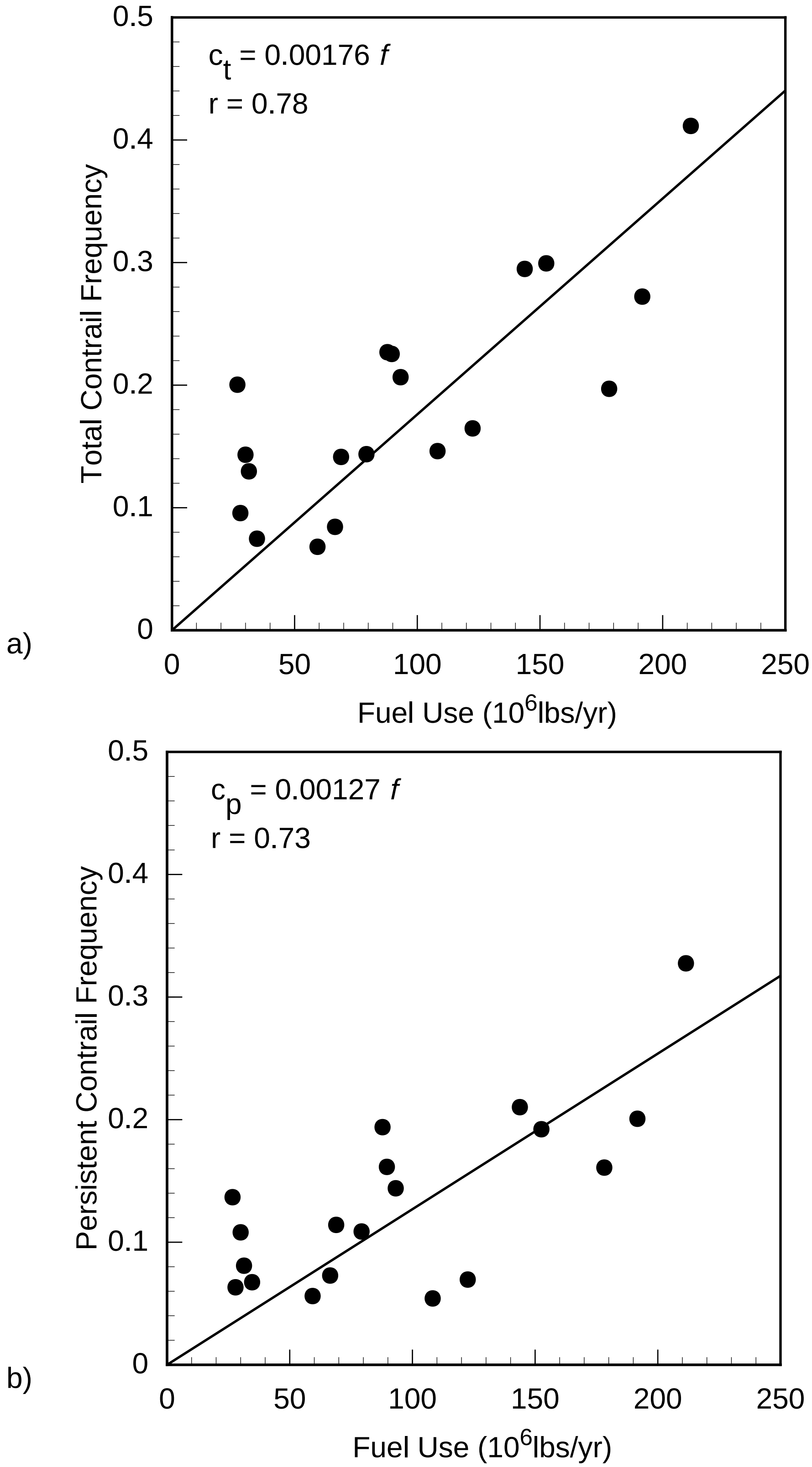


Figure 19. Contrail frequency as a function of fuel use: a) Total contrail frequency. b) Persistent contrail frequency.

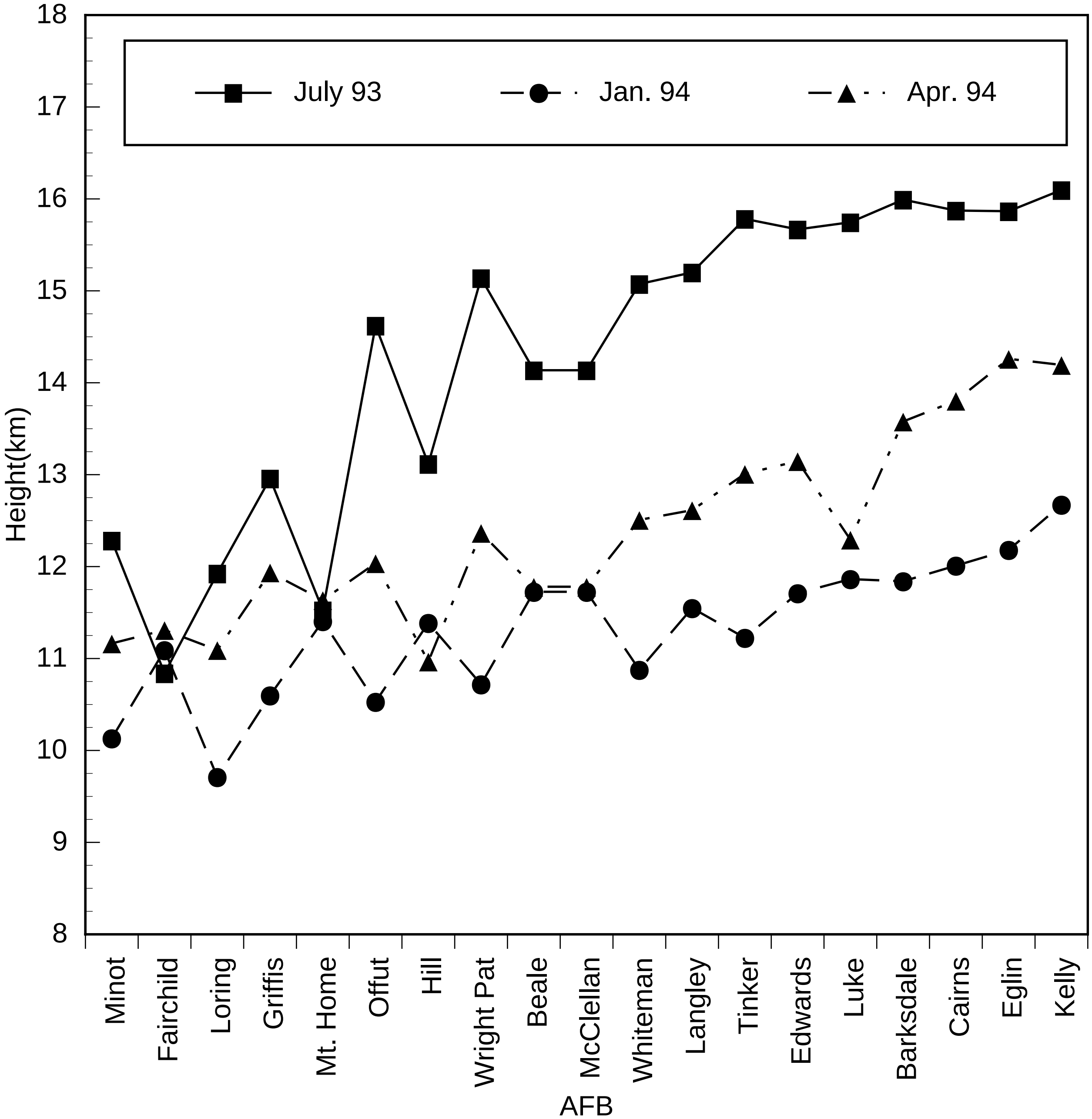


Figure 20. Variation of mean tropopause altitude for July 1993, January 1994, and April 1994. Sites ordered North to South according to latitude.

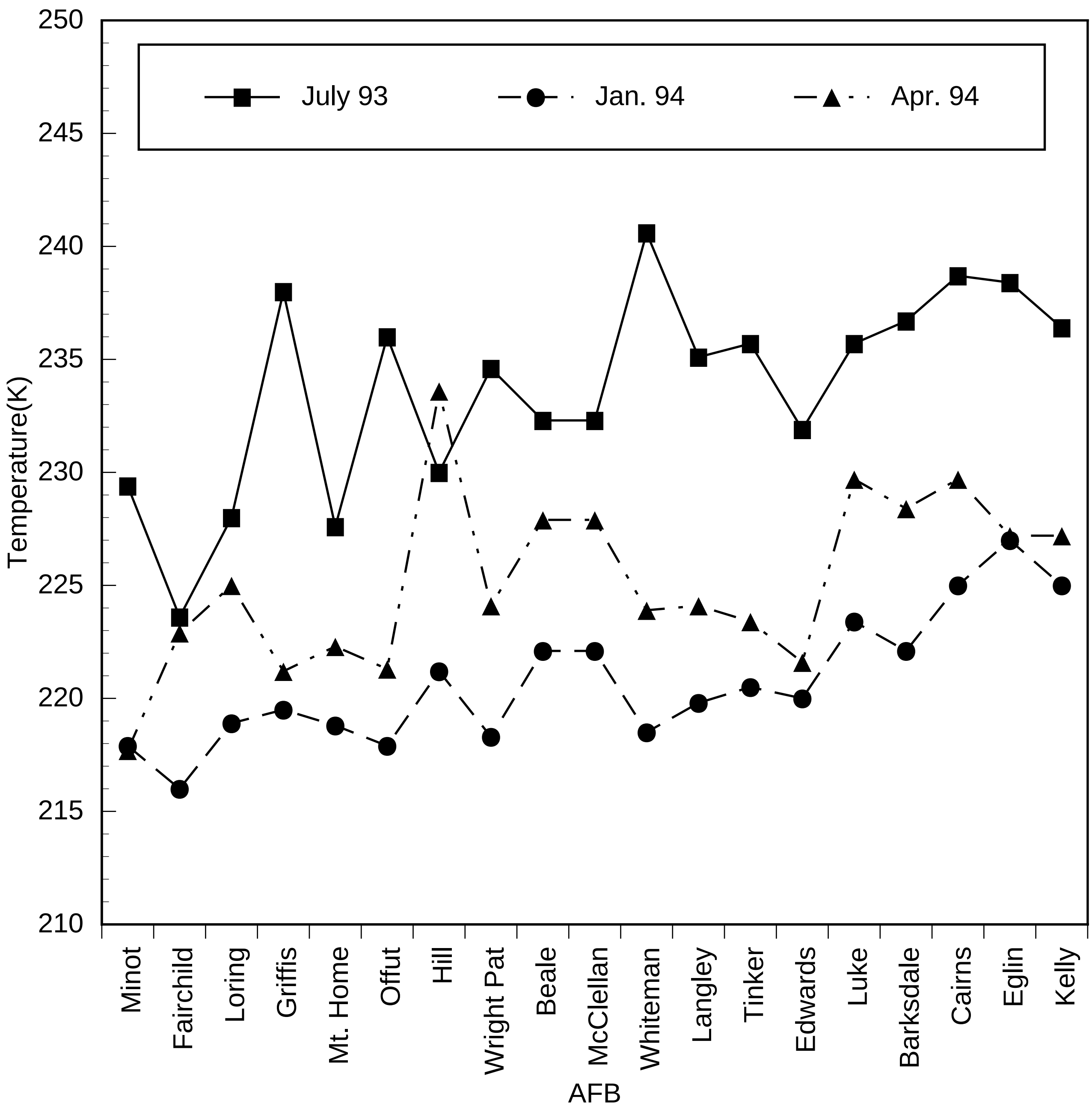


Figure 21. Comparison of temperatures at 10.5 kilometer altitude for July 1993, January 1994, and April 1994. Sites ordered North to South according to latitude.

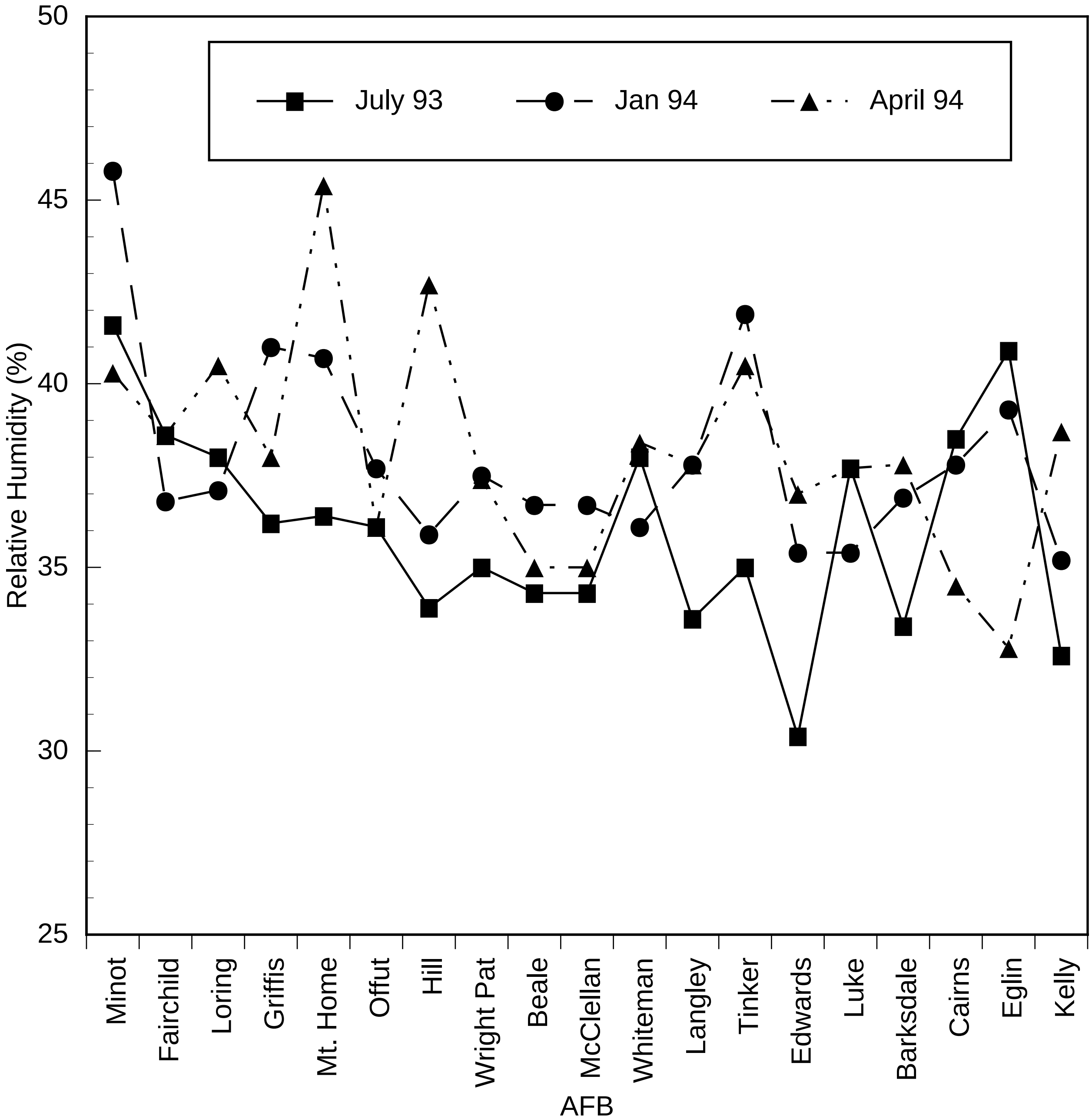


Figure 22. Comparison of mean relative humidities at 10.5 kilometer altitude for July 1993, January 1994, and April 1994. Sites ordered North to South according to latitude.